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PRINCIPLES OF BIODYNAMICS. PROLONGED ACCELERATION: LINEAR AND RADIAL

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Advisory Group for Aerospace Research and Development
Paris, France

1965

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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

64 RUE DE VARENNE PARIS 7e FRANCE

Principles of Biodynamics

Prolonged Acceleration: Linear and Radial

NORTH ATLANTIC TREATY ORGANIZATION

PRINCIPLES OF BIODYNAMICS

As Applied

to

Manned Aerospace Flight

SECTION A

Prolonged Acceleration:

Linear and Radial

FOREWORD

Shortly after the first satellites were earth-orbited in the late Fifties, there was an influx of biomedical investigators in the field of Aerospace Medicine. The Biodynamics Committee of the Aerospace Medical Panel of AGARD-NATO observed in 1961 that, because of the burgeoning of scientific talent into the aerospace biomedical fields, there was a need to inform the new scientists of the basic principles which had been accumulated over many years of earlier aeromedical research. Several things supported this fact; reports in which the investigators apparently were not familiar with related bibliographic data began to appear; projected investigations proposed as new research were often projects which had been successfully carried out by previous investigators; and new terminologies were being formulated with an apparent unawareness of established nomenclatures.

In view of this confused state, younger Flight Surgeons and beginners in aerospace medical research, were justifiably confused as to the state of the aerospace arts and sciences. In an attempt to clarify the confusion that might exist in the area of its own specialty, the Biodynamics Committee of the Aerospace Medical Panel, AGARD-NATO received permission from the Aerospace Medical Panel to compile a "Comparative Table of Acceleration Terminologies," including the then existing six terminologies with the hope of restraining these from being further increased in number.

The Biodynamics Committee concluded that it could be of further assistance in the field of aerospace medicine by compiling a loose-leaf Manual consisting of a series of monographs covering the generally accepted basic information in the field of aerospace biodynamics for the purpose of providing a source of fundamentals for aerospace biomedical personnel in the operational and research fields. It is hoped that it will be possible to include in this Manual sections on:

A. Prolonged Acceleration: linear and radial

B. Angular Motion

C. Impact Deceleration

D. Vibration

E. Combined Stressors

Each of the sections will comprise a number of chapters by experts in the field, covering the terminology, the physics, the physiology, and tolerance limits.

It is hoped that our nominated authors will be able to contribute to this manual, and that the loose-leaf format will allow amendment and extension as contributions are received. Meanwhile, we offer herewith the first section, consisting of four chapters on Prolonged Acceleration, Linear and Radial.

In 1962 the First "Comparative Table of Acceleration Terminology" was compiled by the Biodynamics Committee and widely promulgated. General acceptance of its use was endorsed not only by the Aerospace Medical Panel of AGARD, but by the Aerospace Medical Association, and the National Aeronautics and Space Administration of the United States

Government. In 1965, this Table has been revised to meet the changes that have occurred in the past three years. The new table which replaces the original table is inserted as Chapter 1 of this section of the Biodynamics Manual.

At the time of the Twenty-Second Aerospace Medical Panel meeting in Fuerstenfeldbruck, Germany, in addition to the revised Table of Comparative Terminologies, there were also three monographs ready for publication. The Biodynamics Committee endorses these papers for immediate publication. The first issue of the loose-leaf Manual will thus comprise a single section, but it is felt that it contains enough factual information to make it of value to the student of the applications of biodynamics in Space insofar as linear and radial acceleration is concerned. It is hoped that interest will be stimulated and that suggestions may be made in order that succeeding sections may best fulfil the need which our Committee has envisaged.

Charles F. Gell, M.D., D.Sc.
Chairman, Biodynamics Committee

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CHAPTER I

ACCELERATION TERMINOLOGY

TABLE OF COMPARATIVE EQUIVALENTS

by

G.J.Pesman

ACCELERATION TERMINOLOGY
TABLE OF COMPARATIVE EQUIVALENTS

Several terms are used to describe the direction of an accelerative force applied to the human body or its animal substitutes. In some cases the direction of the applied force or the resulting acceleration of the whole mammal is described. In other cases the kinetic or inertial reaction and the relative movement of body tissues or fluids is used to define the direction of action[1]. As a result a wide range of terms, such as forward acting force, forward acceleration, anterior-posterior kinetic reaction or eyeballs in relative motion is used to describe an identical circumstance. Because of this multiplicity of terms much semantic confusion results.

Attempts to eliminate this confusion have been made. The results are aptly described by the following quotation:

> "The committee on Acceleration of the Aerospace Medical Panel of AGARD has explored the feasibility of establishing a standardized terminology for usage in acceleration studies. After canvassing the international facilities engaged in acceleration research and gauging their response to the recommended terminologies, the committee has come to the conclusion that it is more desirable and practical to assemble a table of equivalents for the terminologies in common use for the easement of translation[2]".

Since its inception in 1961 this table of equivalents has been a very useful tool. The Biodynamics Committee of the Aerospace Medical Panel has maintained that frequent updatings of the original table should be considered when necessary and, in the Committee's opinion, advances in the Aerospace field have now made certain revisions desirable.

The development of vertical or steep landing and take-off aircraft, helicopters, and space vehicles has destroyed the comfortable situation in which the vehicle and occupants maintained a fixed relationship, with the crew and passengers always facing the nose of the vehicle. Under such circumstances essentially synonymous vehicle and human terms could be used for the forces and accelerations imposed on the vehicle and occupants. With the advent of the recent advances cited, however, it is desirable that essentially two directional terminologies be used, one for the vehicle and another for the occupants. Such terms have evolved and, as far as practicable at this time, have been incorporated in revised tables of equivalent terminology for both linear and angular motion.

The members of the Biodynamics Committee determined that the relationship between the directions of the forces applied to the vehicle and the directions of the resulting forces, accelerations, kinetic reactions, and relative motions of the occupants could be simplified by organizing the tables into the form of a statement of the laws of

motion. The resulting tables, then, except for a few other essentially minor changes, preserve the essentials of the previous AGARD table of equivalents and are described in the following paragraphs.

As implied in the previous paragraphs, two tables are provided (Tables I and II). The first table lists the equivalent terms used in describing the various aspects of linear motion, and the second table lists the terms pertaining to angular motion. Each table is divided into two main parts. The left-hand side of the tables describes the coordinate systems and terminology used for various vehicles. The right-hand parts of the tables describe the coordinate systems and terminology used for humans and their surrogates. The figures and coordinate axes shown in the vehicle part of the table show both conventional vehicle axes and axes for space vehicles or VTOL aircraft. No essential difference exists between the two groups except that the coordinate axes of the space vehicle and VTOL craft have been turned 90^{o} with respect to the earth's surface to correspond to the launch or take-off attitudes.

The mammalian terminology has been subdivided into two sections. The first section illustrates and lists the terms that describe the directions of imposed forces and resulting accelerations. The second section illustrates and lists the terms describing the direction of the resulting kinetic or inertial reaction, and the direction of movement of tissue or body fluids relative to the skeletal frame with erect head. The directions listed are defined on the basis of a vantage point located at the intersection of the coordinate axes shown. These coordinate axes correspond to the recommendations made by Clark, Hardy, and Crosbie[1].

The vehicle directional terms listed in column 1 are taken from common usage. No "accepted standard" terms exist for these directions. Port and starboard have been listed in place of left and right because the latter terms are human references and are so used in the human coordinate system. The ASA standard symbols for the directional terms[3] are listed in column 2. The various possible positions that an occupant may take in a vehicle are listed in column 3. The information in columns 1 and 3 must be correlated in order to select the proper corresponding line in the mammalian coordinate system.

The terms used to describe the directions of the force that the vehicle applies to a specific occupant and the direction of the resulting acceleration are listed in column 4. The small figures and arrows further clarify the meaning of the terms listed. There are no accepted symbols for these terms, although the $\pm G_{xyz}$ symbols are occasionally erroneously used. These symbols will be discussed further in connection with columns 5 and 6.

The "tailward" term used in column 4 duplicates a vehicle term and thus can be confusing. The "footward" term, however, is confusing when four-footed animals are used as a human surrogate. Consequently, neither term is completely satisfactory, and a less confusing term for human use will be considered for future incorporation in the tables.

The terms used to describe the direction of the kinetic or inertial reaction that results from the applied force are listed in column 5. These adjectives, when correctly used, should modify "kinetic reaction", "inertial reaction", or "inertial resistance" and not the applied force or acceleration. The kinetic reaction is a force equal to

and opposite in sense to the applied force and cannot be considered an acceleration. The small figures clarify the direction of the specific kinetic reaction.

The $\pm G_{xyz}$ symbols listed in column 6 also represent kinetic reactions[1,2], not accelerations, as the letter G tends to imply. Thus a phrase such as "$-G_z$ acceleration" is a misnomer and creates additional confusion.

The terms that are used to describe the motion of tissues, organs, and body fluids relative to the erect head and skeletal frame are listed in columns 7 and 8. The "eyeballs" terminology, column 7, is now commonly used by test pilots and design engineers. For correct interpretation the head must be in the normally erect position. The meaning of the relative heart movement terms in column 8 is essentially obvious from the small inset figures.

The physical relationship between the terms in the various columns is shown by the two sentences enclosed in the boxes between columns. The terms in the columns combined with the words in the boxes form the two sentences. For example for a tailward facing passenger in a conventional vehicle; an acceleration "noseward (symbol $+a_x$)" of the vehicle with the occupant "facing 'tailward'" with respect to the vehicle axes, imposes a "backward" acceleration on the occupant. Because of this accelerative force the

occupant's body instantaneously produces an opposing " transverse P-A / prone / back to chest kinetic

reaction or inertial resistance (symbol $-G_x$)" and "eyeballs out" or "forward heart movement" relative to the erect head and skeletal frame.

The format of the table of angular motion equivalents is similar to the linear motion table. Since the small figures in column 4 show clearly the direction of rotation associated with the various terms, the coordinate system figure has been deleted. This deletion produces no problems because symbols have not been established for physiological moments and angular motion.

To prevent the confusion that is inevitable if vehicle terms are used to describe, human motions, terms from the sports field have been suggested for human rotation or tumbling. Consequently, the terms cartwheel, somersault, and twist have a long history of lay usage. It is strongly suggested that these terms be used instead or roll, pitch, and yaw when discussing human or mammalian rotation.

The tables described are the joint effort of personnel from the Biodynamics Committee. These men are as follows:

C.F.Gell, M.D., D.Sc.

F.E.Guedry, Ph.D., USN

A.S.Hyde, Ph.D., M.D.

G.J.Pesman

C.C.Clark, Ph.D.

A.G.Swan, Colonel, USAF, Ph.D.

Mr Pesman, with the services and cooperation of various NASA Manned Spacecraft Center Groups, coordinated details and updated, revised, and prepared text, figures and tables with the concurrence and support of the Biodynamic Committee

REFERENCES

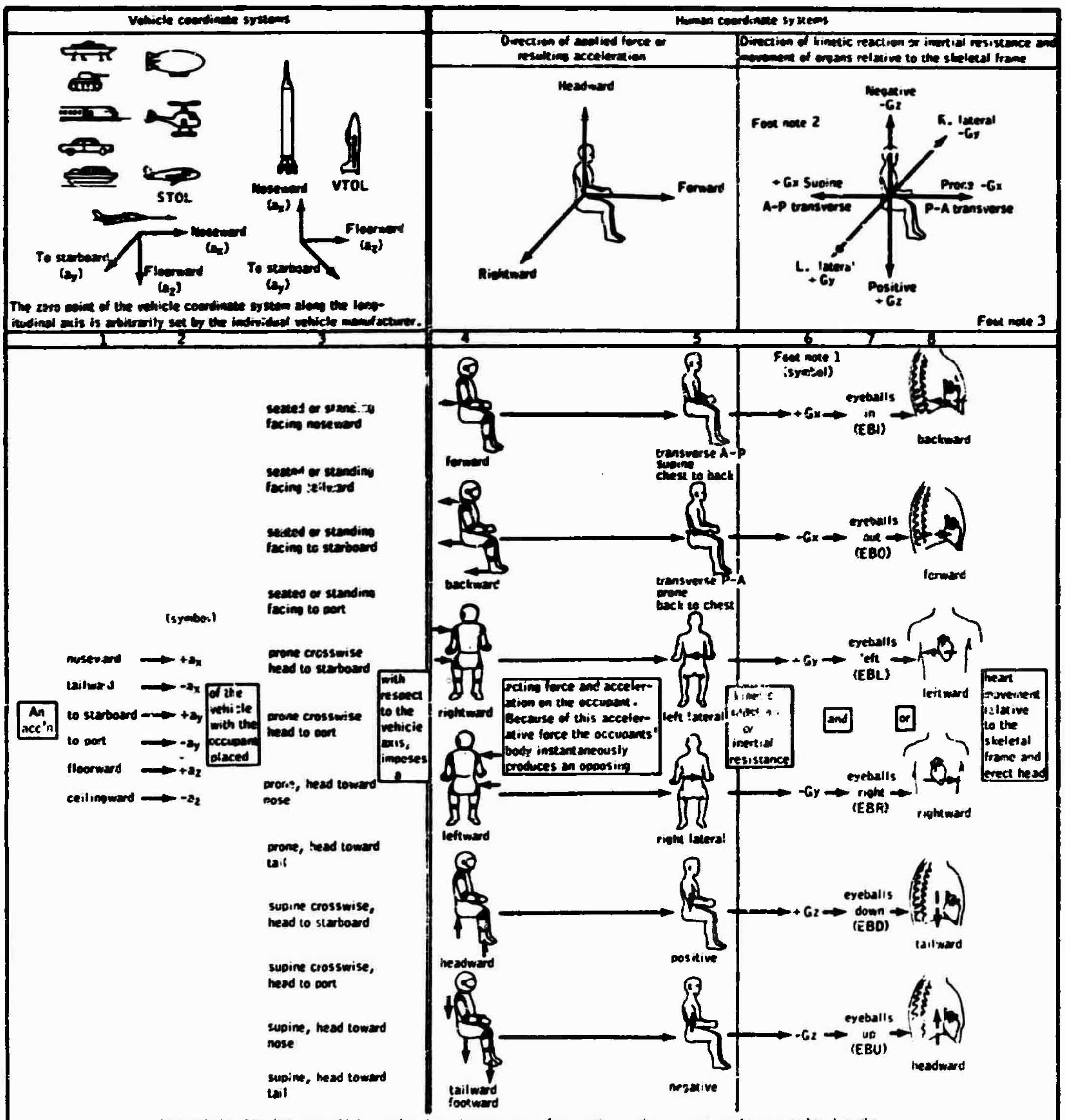
1. Clark, Carl C. et al. — *Human Acceleration Studies Terminology*. National Academy of Sciences, National Research Council Publication 913, 1961.

2. Gell, C F. — *Table of Equivalents for Acceleration Terminology*. Aerospace Medicine, Vol. 32, Dec. 1961, pp. 1109-1111.

3. - — Sectional Committee on Letter Symbols: *Letter Symbols for Aeronautical Sciences*. Published by American Society of Mechanical Engineers, ASA Y10. 7, 1954.

TABLE I

Acceleration terms - table of equivalents
Linear motion



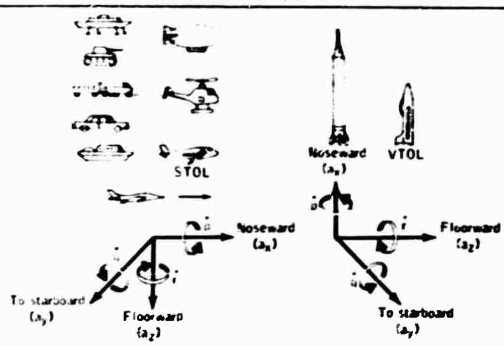
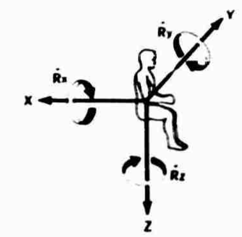
Inter-relationships between vehicle acceleration, the consequent force acting on the occupant, and terms used to describe directions of these variables are shown in the table. Possible inter-relationships are derived as follows: Direction of the vehicle acceleration, based on the above vehicle coordinate system, is selected in column 1. Position of an occupant with respect to the vehicle is selected in column 3. Direction of force acting on vehicle, column 1, combined with the occupant's position with respect to vehicle, column 3, determines direction of force with respect to occupant. Result then determines proper relationship to be selected in column 4. Once correct selection has been made, the two sentences, reading from left to right, list terms and symbols in present use describing directions of forces and accelerations of body, and organ movement relative to skeletal frame. Sentences also describe relationships that must exist because of Newton's laws of motion.

Footnotes:

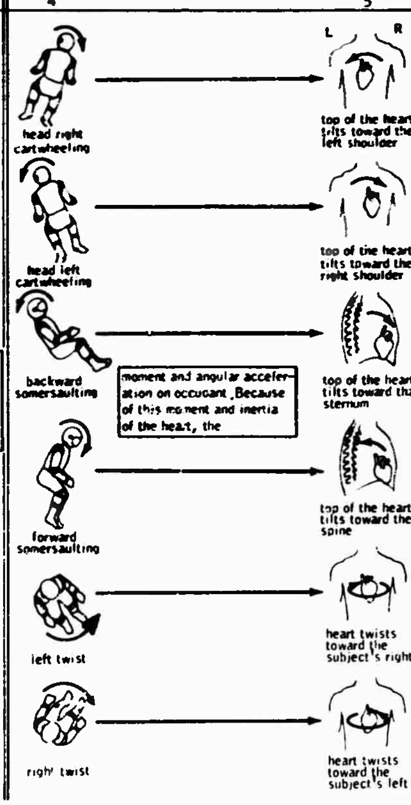
1. Large letter, G, used as unit to express whole body acceleration in multiples of the acceleration of gravity. Acceleration of gravity, $g_0 = 980.665$ cm/sec^2 or 32.1739 ft/sec^2.
2. A-P, P-A refers to anterior-posterior, posterior-anterior.
3. Symbols ($\pm$Gxyz) represent orthogonal directions of kinetic reaction opposing applied force and thus units must be pounds of reaction force per pound of involved object. Laws of motion indicate that "G" may not represent an acceleration in situations and context depicted, and statement "a + Gx acceleration" would be a misnomer.

TABLE II

Acceleration terms - table of equivalents
Angular motion

Vehicle coordinate systems	Human coordinate system
 The zero point of the vehicle coordinate system along the longitudinal axis is arbitrarily set by the individual vehicle manufacturer.	 Direction of heart rotation relative to skeletal frame

1		2	3		4		5	6 *
	(symbol)		seated or standing facing noseward		head right cartwheeling		top of the heart tilts toward the left shoulder	
			seated or standing facing tailward					
			seated or standing facing to starboard		head left cartwheeling		top of the heart tilts toward the right shoulder	
			seated or standing facing to port					
right roll	$\dot{p}$		prone crosswise head to starboard		backward somersaulting		top of the heart tilts toward the sternum	
left roll	$-\dot{r}$		prone crosswise head to port					
A positive pitch	$\dot{q}$	of vehicle with occupant placed	prone, head toward nose	with respect to vehicle axis, imposes a	forward somersaulting	moment and angular acceleration on occupant. Because of this moment and inertia of the heart, the	top of the heart tilts toward the spine	
negative pitch — angular acceleration	$-\dot{q}$		prone, head toward tail					
right yaw	$\dot{r}$		supine crosswise, head to starboard		left twist		heart twists toward the subject's right	
left yaw	$-\dot{r}$		supine crosswise, head to port					
			supine, head toward nose		right twist		heart twists toward the subject's left	
			supine, head toward tail					



The inter-relationships between vehicle acceleration, the consequent force acting on occupant, and terms used to describe directions of these variables are shown in table. These various possible inter-relationships are derived as follows. Direction of vehicle acceleration, based on above vehicle coordinate systems, is selected in column 1. Position of occupant with respect to vehicle is selected in column 3. Direction of force acting on vehicle, column 1, combined with occupant's position with respect to vehicle, column 3, determines direction of force with respect to occupant. This result then determines proper relationship to be selected in column 4. Once correct selections have been made, the two sentences, reading from left to right, list terms and symbols in present use to describe the directions of forces and accelerations of body and organ movement relative to skeletal frame. Sentences also describe relationships that must exist because of Newton's laws of motion.

* Footnote:
Statements true only when intersection of axes is below heart.

PRINCIPLES OF BIODYNAMICS

As Applied

to

Manned Aerospace Flight

PROLONGED ACCELERATION: Linear and Radial

CHAPTER II

AN INTRODUCTION TO THE PHYSICS AND PHYSIOLOGY OF ACCELERATION

by

S.D.Leverett, Jr

AN INTRODUCTION TO THE PHYSICS AND PHYSIOLOGY OF ACCELERATION

1. FUNDAMENTAL PRINCIPLES INVOLVED

1.1 Introduction

1. In the days of frail canvas-covered aircraft which flew at slow speeds and which could not take stresses easily tolerated by the human body, acceleration was not much of a problem. Today, aircraft of much stronger construction travel at sonic and supersonic speeds and thus can impose tremendous forces for appreciable periods of time on the now relatively frail human occupants.

2. History of acceleration and its relation to aviation medicine.

(a) 1818 - Charité Hospital, Berlin. First large centrifuge used therapeutically for treatment of mental disorders.

(b) L.Hill - 1895 - Effects of gravity on circulation.

(c) Dr A.P.Thurston - 1903 - First man to experience blackout and unconsciousness in the air (while riding a rotating carnival machine).

(d) Dr P.Garsaux - 1918 - First aeromedical experiments accomplished on a centrifuge using dogs.

(e) Pulitzer Air Races - 1922-23.

(f) Capt. Luke Christopher, Air Corps Reserve, 1928 - First man to be hospitalized as a result of overexposure to acceleration (10.5 G).

(g) Jongbloed and Noyens - 1934 - Classic cardiovascular studies on rabbits exposed to centrifugation.

(h) German Centrifuge, 1934 - First human centrifuge constructed for aeromedical research.

3. The physiological effects and the clinical response to such forces obviously should be understood by the Flight Surgeon.

4. The conventional terminology for discussing these forces and their effects must first be established.

(a) *Speed* - The rate of motion of an object. It is a scalar quantity having magnitude only.

$$\text{Speed} = \frac{\text{distance}}{\text{time}};\ \frac{\text{miles}}{\text{hr.}};\ \frac{\text{feet}}{\text{sec.}}$$

(b) *Velocity* - The rate of directed motion of an object. It is a vector quantity having both magnitude and direction. The velocity of a body changes if it changes *direction, speed,* or *both.*

(i) If velocity is constant, then

$$\text{distance} = \text{velocity} \times \text{time}$$

$$s = Vt \quad \text{or} \quad V = \frac{s}{t} .$$

(ii) If velocity is increasing or decreasing at a constant rate,

$$\bar{V} = \frac{V_2 + V_1}{2} ,$$

Where

Where $\bar{V}$ = average velocity
V_2 = final velocity
V_1 = initial velocity.

(c) *Acceleration* - The time rate of change of velocity. It is also a vector quantity.

(i) *Linear acceleration* - An acceleration in which only a change in velocity is involved.

$$a = \frac{V_2 - V_1}{t} \quad \text{or} \quad \frac{\Delta v}{t} .$$

Multiplying both sides by t ,

$$V_2 - V_1 = at .$$

Transposing V_1

$$V_2 = V_1 + at .$$

Thus it can be seen that the final velocity V_2 is the sum of the two terms V_1 (initial velocity) plus the increase in velocity, at . If you start from rest, the inital velocity V_1 is equal to 0 and the equation is

$$V_2 = at$$

or

$$a = \frac{V_2}{t} \text{ or just } \frac{V}{t} .$$

In a previous equation, we said that if the velocity were constant, then $s = Vt$; this also holds true for constant acceleration if V is replaced by $\bar{V}$. We have already defined $\bar{V} = V_2 + V_1/2$ as being the average velocity, thus

$$s = \bar{V}t \quad \text{or} \quad s = \frac{(V_2 + V_1)t}{2} .$$

The above equations and definitions of acceleration, speed, and velocity are the only *true equations* for linear motion. All other equations are called *derived equations* and are in fact derived from combinations of the two equations:

$$a = \frac{V_2 - V_1}{t}$$

and

$$s = \frac{(V_2 + V_1)t}{2}$$

Solve each equation equal for t :

$$t = \frac{V_2 - V_1}{a} \quad \text{and} \quad t = \frac{2s}{V_2 + V_1} .$$

Then

$$\frac{V_2 - V_1}{a} = \frac{2s}{V_2 + V_1}$$

$$(V_2 - V_1)(V_2 + V_1) = 2as ,$$

then

$$V_2^2 - V_1^2 = 2as$$

or

$$V_2^2 = V_1^2 + 2as .$$

Also

$$a = \frac{V_2^2 - V_1^2}{2s} .$$

This equation would express the acceleration imparted to a body in which there was an initial velocity.

Again, combine the same two equations but this time set each equal to V_2 .

$$V_2 = V_1 + at \quad \text{and} \quad V_2 = \frac{2s}{t} - V_1 .$$

Then

$$\frac{2s}{t} - V_1 = V_1 + at .$$

Transposing,

$$\frac{2s}{t} = 2V_1 + at .$$

Multiply both sides by $\frac{t}{2}$:

$$s = V_1 t + \tfrac{1}{2}at^2$$

When a body is initially at rest $V_1 = 0$, then the derived equations become

$$\text{(a)} \quad V_2^2 = 2as \quad \text{or} \quad a = \frac{V_2^2}{2s}$$

$$\text{(b)} \quad s = \tfrac{1}{2}at^2 .$$

(ii) *Radial Acceleration* - A body moving along a straight line has its *speed* and *velocity* numerically equal to each other. However, a body moving in a curved path with a constant speed is constantly changing direction; thus, in our previous definition of velocity, we said velocity changed if its direction changed; so a constant speed but always changing direction. Therefore, the acceleration is due to the velocity constantly changing direction. The direction of the acceleration is perpendicular to the direction of velocity, i.e., towards the center of the circle, and this is called *centripetal acceleration*. Radial acceleration involves only a change in direction.

$$a = \frac{V^2}{\text{radius of turn}}$$

(iii) *Angular Acceleration* - Involves a change in both speed and direction simultaneously.

(d) *Force* - A push or pull exerted on a body to produce an acceleration. It is a vector quantity having magnitude and direction.

(e) *Mass* - The quantity of matter.

(f) *Weight* - The force exerted on a given mass by the pull of gravity. Weight is a force, mass is a quantity. Weight can only exist in a "gravitational" field. By convention, the weight of an object at rest on the surface of the earth is numerically equal to its mass. During any acceleration an additional "gravitational" field is temporarily established, as for example, on a centrifuge (radial acceleration), and weight changes; mass always remains constant.

(g) *Inertia* - The resistance offered by an object to a change of its state of rest or motion. A fundamental property of mass. It is this inertial resistance during an acceleration that manifests itself as *weight*.

(h) *Inertial Force* - (inertial resistance) - is equal, but opposite to *accelerative force*. It is the inertia of the human body that actually causes the physiological effects during an acceleration.

(i) *Centripetal Force* - The force required to keep a moving object in a circular path; the accelerative force in radial acceleration.

(j) *Centrifugal Force* - The outward force of an object or body in rotation; the inertial force that is equal and opposite to the centripetal (accelerative force). The centrifugal force is the important force physiologically.

1.2 Essentials of Motion

1. The essentials of acceleration are based on Newton's three fundamental laws of motion.

2. *Newton's first law* states that a body at rest will remain at rest and a body in motion will move at a constant speed in a straight line unless acted upon by a force.

(a) Thus a force is required to change the existing state of rest or motion of a body.

3. *Newton's second law* states that when a force is exerted upon a body, the body is accelerated and the acceleration is directly proportional to the force applied, and is inversely proportional to the mass of the body.

$$a = F/m \quad \text{or} \quad F = ma .$$

(a) The magnitude of the force during an acceleration is the important determination physiologically.

(b) The equation $F = ma$ is the basic mathematical expression of Force.

(c) The force can be calculated if m and a are known. It is necessary, in the calculations, to maintain the correct proportionality by converting the appropriate terms to either pounds, feet, seconds, or to grams, centimeters, seconds.

(i) Since $a = (V_2 - V_1)/t$ then $F = m(V_2 - V_1)/t$ for a linear accelerative force.

(ii) Since $a = V^2/r$, then $F = mV^2/r$ for a radial accelerative force.

(d) Thus, in the case of linear acceleration the force can be determined if the velocities and time are known (for example, in a crash landing). Usually, however, in aircraft accidents, the *time* during which the deceleration occurs is never directly known. However, the *distance* over which a crash occurs can often be measured. The greater the distance covered during a change in velocity, the greater is the time involved. Both *time* and *distance* are inversely proportional to the accelerative force.

(e) In the case of radial acceleration, the force can be determined if the velocity and radius of the curve are known (for example, when a pilot executes a high speed turn).

4. *Newton's third law* states that for every action there is an equal and opposite reaction. This means that for every accelerative force there is an equal and opposite inertial force.

(a) Thus, if an accelerative force is known, as can be determined from the above equations, the inertial force is also automatically known, except that the two forces act on the body in opposite directions. This does not mean that a person can pull himself up by his bootstraps or that the forces cancel each other out. The accelerative force is caused by the force of another object acting on the body (an accelerating plane pushes the aviator forward), the inertial force is the resistance of the body acting against the accelerative force.

5. In the Air Force, and in aviation in general, it has been found convenient to measure accelerative forces in *gravitational* units called G.

(a) When a force is measured in terms of gravity, it is a weight.

(b) The acceleration of a falling body due to the pull of the earth's gravity is 32.2 ft/sec^2 and is called one "g".

(c) Every object or person at rest on the surface of the earth is always under a potential acceleration of one "g".

(d) The force of this constant gravitational pull is normal weight = mass.

(e) If an object should be accelerated at a rate of 64.4 ft/sec^2, the accelerative force = 2G, and the object's weight during the acceleration would be twice its normal weight or twice its mass.

(f) Accordingly, an acceleration of 10G (322 ft/sec^2) increases the weight ten times, 20G, 20 times, etc.

(g) Thus, $W = ma/G$, where $g = 32.2$ ft/sec^2 or $W = m \times G$ units .

6. *Summary*

(a) The motion of a body is expressed in terms of velocity which involves both speed and direction.

(b) If either or both of the two components of velocity are changed, acceleration must take place.

(c) A force is required to produce an acceleration.

(d) The force is directly proportional to the mass and to the acceleration.

(e) The force is inversely proportional to the time and to the distance covered during an acceleration (linear).

(f) The force is proportional to the square of the velocity and inversely proportional to the radius of turn during radial acceleration.

(g) When a force acts on a mass, the weight of the mass is proportional to the force, but is manifest in the opposite direction of the force (inertial force).

(h) Force may be expressed in terms of "G" units, one G being equal to the potential acceleration due to the earth's gravity, 32.2 ft/sec^2. Under one G, weight = mass, numerically.

(i) The change in weight as the result of an imposed force (acceleration) is calculated by: $W = m \times G's$.

1.3 Types of Acceleration in Relation to the Motion of Aircraft

1. *Linear Acceleration*

(a) As already stated, this involves only a change in speed along a straight course.

(b) Not a great problem at present except in aircraft accidents and emergency escapes. But may be one of the limiting factors during manned rocket take-off's in the future, for example.

(c) Aircraft accidents and crashes and emergency escapes from high-speed planes involve linear accelerations that can be of very high magnitude, but which last for only brief periods of time (fractions of a second).

(d) In flying, linear accelerations occur in take-offs and landings.

(e) Greater linear accelerations occur in:

(i) Catapult take-offs.
(ii) Jet assisted take-offs.
(iii) "Pick-ups" by aircraft.
(iv) Arrested landings (aircraft carriers).
(v) Ditching.
(vi) Parachute-opening shock.
(vii) Ejection seat escapes.
(viii) High-speed bailouts.
(ix) Crashes.

(f) Measurement of linear acceleration in G units: By mathematical derivation it can be shown that

$$G's = (V_2^2 - V_1^2)/2gs \text{ ,}$$

where V = velocity in feet/second
$g = 32.2$ ft/sec^2
s = distance in feet over which acceleration occurs.

Weight of aviator during acceleration = aviator's mass × G's.

2. *Radial Acceleration*

(a) As already stated, this type of acceleration deals only with a change in direction, and the speed may be considered constant.

(b) Radial accelerations involve forces of moderate magnitude (up to 10G), but which last for appreciable lengths of time (several seconds to minutes).

(c) Since radial accelerations occur during normal combat maneuvers, the effect on the human body is the chief acceleration problem in military aeronautics and aviation medicine today.

(d) Radial accelerations occur in:

(i) Banks and turns.

(ii) Pull-outs from dive.

(iii) High-speed nose-overs.

(iv) Loops and rolls.

(e) Measurement of radial acceleration in G units:

(i) It can be shown that the acceleration needed to maintain a body on a circular path of motion is directly proportional to the *square* of the velocity and inversely proportional to the radius of the turn.

$$a = V^2/gr \ .$$

(ii) Further derivation provides us with a formula for calculating radial acceleration in "G" units.

$$G's = V^2/gr \ ,$$

where V = velocity in circumferential ft/sec

g = 32.2 ft/sec^2

r = radius of turn in feet

Again, pilot's weight = mass x G's

3. *Angular Acceleration*

(a) It is not necessary to consider angular acceleration in order to analyze the main physiological effects of acceleration in general.

(b) Angular acceleration may be one of the important factors in motion sickness.

(c) Angular acceleration, of course, occurs almost all the time, to some degree, in moving aircraft.

(d) Angular acceleration occurs particularly in

(i) Spins.

(ii) During flights through storms, "bumpy" weather, etc.

(iii) Tumbling, following bailout from aircraft.

2. THE PHYSIOLOGICAL EFFECTS OF ACCELERATION

2.1 Introduction

1. *Factors that determine the effect of accelerative forces on man.*

(a) The degree (intensity) of the acceleration.

(b) The time (duration) of application.

(c) The rate of application.

(d) The area and site over which the force is applied (i.e., to the body).

(e) The direction of the accelerative force with respect to the long axis of the human body.

2. *Terminology necessary for analyzing the physiological effects of acceleration on the human body.* During early human centrifuge studies, the terms describing the effects of acceleration were directed to the body. For example, positive G physiologically resulted in a pooling of blood in the lower extremities while negative G caused a shift of blood to the head region. With more centrifuges coming into operation, the confusion became rampant in describing the resultant accelerative or inertial forces acting on the body. An unsuccessful attempt was made to standardize terminology; thus it became necessary to produce a Comparative Table of Equivalents which would simply list all methods of describing the forces. For the purposes of this review, the $\pm G_x$, $\pm G_y$, $\pm G_z$ terminology will be used to describe Transverse, Lateral Transverse, and Positive G, and Negative G, respectively. See Acceleration Terminology AGARDogram Number 1 for further definition of terms.

2.2 How Factors Operate to Produce Effects of Acceleration

1. *The Effect of Intensity of the Acceleration*

(a) In general, the greater the intensity, the more severe the effects.

(b) However, intensity alone does not tell the whole story. A flyer undergoing 12G in a tight turn would be rendered unconscious within two seconds. Yet, a person can undergo 12-15G by jumping off a table 4 ft high with no harm at all.

(c) The time, or duration, of application is obviously involved to determine what effect a given intensity will produce.

2. *Length of Time Force is Applied*

(a) In general, the longer the force is applied, the more severe the effects.

(b) Five G for 2-3 seconds, harmless; 5G for 5-6 seconds causes "blackout" and possibly unconsciousness.

(c) Headward acceleration in ejection seat is 15G for about 0.2 seconds without harm. Fifteen G for 2 seconds causes unconsciousness.

(d) Forty G intermittently for a fraction of a second each time during a crash landing can be tolerated. If it is steady for 2-3 seconds - crunch!

(e) It is obvious that extremely short periods of application enables a body to absorb large forces without harm.

(f) It can generally be stated that unless a force is so great that it overwhelms and stuns a man outright, the force must act for a considerable length of time to produce any effect at all, i.e., for several seconds.

3. *Rate at Which Force is Applied*

(a) In general, the higher the rate of application, the more severe the effects.

(b) However, an extremely large force, no matter how slowly applied, can do damage, i.e., a steam roller.

(c) Thus, *impact* and *pressure* are entirely different.

(d) The rate of application is often slowed down in plane crashes by crumpling of the wing and nose, giving 3-4 extra feet in which to decelerate.

(e) Thus, the *distance*, as well as the *time*, over which a giv acceleration occurs is an important factor.

4. *The Area and Site on the Body over Which the Force is Applied.*

(a) The greater the area over which a given force is distributed, the less harmful are the effects.

(b) Consider the comfort and safety afforded by a wide seat belt or strap as compared to a narrow strap during an abrupt deceleration.

(c) Also, the site on the body over which a force is applied is important when considering accelerative effects.

(d) It is obvious that a given force or blow to the head can be much more serious than the same force applied to some other part of the body.

5. *The Direction of the Accelerative Force with Respect to the Long Axis of the Body.*

(a) The direction that a prolonged accelerative force acts on the body determines what physiological effects will occur.

(b) At the present time, prolonged accelerations during aircraft flights are caused mainly by radial accelerations. The physiological effects are the result of the centrifugal force and the increased weight of the body (and its component parts).

(c) The effects of radial accelerations on the body have been studied extensively by the Air Force on large, specially constructed, human centrifuges.

(d) $+G_z$ *Acceleration* (Positive G or Headward Acceleration) means that the aviator is accelerated in a headward direction by the centripetal force. The *centrifugal force*, the force that the aviator is aware of, acts in the opposite direction toward the feet. Common examples are during a pullout from a dive or when a pilot executes a high-speed bank and turn.

(e) $-G_z$ *Acceleration* (Negative G or Footward Acceleration) occurs when the accelerative force acts on the body in a footward direction. In this case, the centrifugal (inertial) force is toward the head. Typical examples are during a nose-over and an outside loop.

(f) $+G_x$ *Acceleration* (Forward Transverse G) occurs when the accelerative force acts across the body at right angles to the long axis in a back-to-chest direction. The centrifugal force would also be across the body, but in the opposite direction or in a chest-to-back direction. An astronaut lying semi-supine in a special couch is exposed to $+G_x$ acceleration during exit and also during re-entry. It occurs during re-entry without a shift in the couch due to rotation of the entire spacecraft to expose the heat shield to denser atmosphere. A pilot seated upright in aircraft such as the X-15 or propcsed Dynasoar also are exposed to $+G_x$ acceleration during the exit or firing phase of the flight profile.

(g) $-G_x$ *Acceleration* (Backward Transverse G) occurs when the accelerative force acts across the body at right angles to the long axis in a chest-to-back direction. The centrifugal force would also be across the body in a perpendicular direction but in a back-to-chest direction. Piloting aircraft such as the X-15 or Dynasoar during the re-entry phase of the flight would expose the astronaut to $-G_x$ acceleration. He is forced forward against his straps and has a tendency to be pitched out of his seat unless tightly restrained.

(h) $\pm G_y$ *Acceleration* (Right or Left Lateral Transverse G) Accelerations of this type are encountered only briefly in normal flight and never in space flight unless an emergency situation arose in which the space craft was exiting or re-entering in a non-stable manner.

2.3 The Physiology of Prolonged Acceleration (usually radial accelerations, centrifugal force).

1. Prolonged accelerations are usually of moderate magnitude - up to 10-15G and lasting for at least several seconds.

(a) *The cardiovascular system* is the main component of the body that is primarily affected by excessive G forces during aircraft maneuvers.

(b) The skeleton and semi-solid tissues of the body can withstand such stresses without trauma.

(c) However, the circulation, supported by elastic blood vessels and depending for its normal function on well-defined pressures and volumes, is grossly disturbed by excessive gravitational forces (prolonged accelerations).

(d) The cerebral spinal fluid, which can also be considered as a hydrostatic fluid column, is also affected by G forces.

2. *The Effects of* $+G_z$ *Acceleration* (Positive G)

(a) The physiologically important inertial force acts in a *footward* direction, from head to feet.

(b) Tremendous stress occurs on suspensory tissues as body organs increase in weight (heart, lungs, diaphragm, abdominal viscera, etc.).

(c) The cardiovascular system fails to supply the head and brain with an adequate blood flow.

(d) *Subjective Effects* (usual sequence of events during build-up to $+7\text{-}10G_z$).

$+1G_z$: Ordinary sensation of one's arm weight, normal body weight, etc.

$+2G_z$: Moderate compression into seat. Some heaviness of limbs and head. Difficult to move about or bail out of plane.

$+3G_z$: Extreme heaviness of limbs and body. Impossible to move or escape from aircraft.

$+3$ to $4G_z$: Dimming or "graying" of vision.

$+3.5$ to $4.5G_z$: Loss of peripheral vision, central light very dim. Can probably be called blackout.

$+4$ to $5.5G_z$: Complete loss of vision - "blackout". Hearing persists, mental orientation good. Symptoms will be as great as they are going to be within 10 seconds. Often after 6-10 seconds, compensatory mechanisms may clear vision deficiency. If force ceases, vision returns in 3 to 5 seconds. Subjectively, an exposure to $+5G_z$ for 4 minutes can be tolerated.

$+4.5$ to $6G_z$: Loss of consciousness (after about 6 seconds).

$+7$ to $10G_z$: Effects appear more rapidly. If force greater, immediate stunning occurs.

(e) Rate of onset of G-force.

(i) Two G per second or less, full sequence seen by pilot.

(ii) Three to 10G per second, may overwhelm pilot, hence unconsciousness before "blackout" experienced.

(f) Unconsciousness due to $+G_z$.

(i) "Blackout" is not unconsciousness.

(ii) Aviator may have dreams or nightmares during unconsciousness.

(iii) After acceleration ceases, recovery from unconsciousness is slow, 15 to 60 seconds.

(iv) For another 15 to 60 seconds, disorientation may exist. Spontaneous clonic movements may occur. Danger of this situation is obvious. Loss of consciousness should be avoided at all costs, particularly in combat.

(g) Objective Effects of $+G_z$ Acceleration (Positive G)

(i) Sagging of soft tissues (cheeks, etc.).

(ii) Lowered blood pressure above the heart, both arterial and venous, as well as cerebral spinal fluid pressure. Venous and cerebral spinal fluid pressures become subatmospheric.

(iii) Increased blood pressure and pooling of blood in lower extremities and below the heart.

(iv) Increased heart rate (tachycardia because of carotid sinus reflex).

(v) Decreased venous return to the heart.

(vi) Decreased cardiac output.

(vii) Circulation to the eye fails first before the cerebral circulation because of the intraocular pressure which normally exists in the eyeballs.

(viii) Respiration speeded at first, but then may be held in inspiratory position because of downward pull of diaphragm.

(ix) All moveable organs, including heart, displaced downward.

(x) Fractures of the lumbar vertebrae have been reported in rare instances.

(xi) Rarely does pull on viscera cause serious displacement.

(xii) Electrocardiograms show changes from the normal pattern during positive G (decreased amplitude and occasional inverted T waves), but this cannot be regarded as evidence of permanent or dangerous cardiac damage.

(xiii) Electroencephalograms are usually normal until the cerebral circulation fails, with the onset of unconsciousness, when hypoxic encephalographic disturbances appear.

(xiv) Decreased binocular visual acuity with increasing $+G_z$ acceleration.

(xv) Atelectasis resulting in decreased arterial oxygenation.

(h) *Mechanism of Chief Effects of Headward Acceleration*

(i) The main symptoms are due to changes in the circulation of the blood.

(ii) The distance from the heart to the brain is, on the average, about 30 centimeters.

(iii) In a sitting position, the blood, in its main vessels from the heart to the brain, can be considered as a column of fluid 30 cm high.

(iv) The hydrostatic pressure of such a column is normally (1G) equal to about 25 mmHg.

(v) A mean arterial blood pressure of 100 mmHg at heart level is normally decreased to 75 mmHg at the level of the brain, because of the 25 mmHg hydrostatic pressure that must be overcome.

(vi) Thus, at 4G the mean arterial pressure at brain level would be reduced to zero, if the arterial pressure at heart level remained unchanged, since the hydrostatic pressure opposing the blood flow would have increased four times, to 100 mmHg.

(vii) Although 4G imposes a heavy load on the circulation above the heart, consciousness is usually not lost at less than 5G for the following reasons:

(a) The *venous* pressure, and the cerebral spinal fluid pressure, drop considerably below atmospheric pressure within the skull, in the order of -30 mmHg or more; thus, although at 4G the arterial pressure might be close to zero at brain level, the *pressure gradient* between the cerebral arteries and veins is still adequate for cerebral blood flow. This has been termed the "jugular suction effect".

(b) The drop in arterial pressure above the heart initiates the carotid sinus reflex which results in an increased heart rate and a generalized peripheral vasoconstriction in an effort to increase the blood pressure above the heart and the cerebral blood flow.

(viii) However, these protective reflexes are usually not adequate during an acceleration of $+5G_z$ or more for the following reasons:

(a) Simultaneously with the drop in arterial and venous pressure above the heart, the blood is forced toward the lower part of the body, resulting in:

1. Increased blood pressure *below* the heart (both arterial and venous).
2. Decreased venous return to the heart.
3. Eventual "pooling" of blood below the heart and decreased circulating blood volume.
4. Decreased cardiac output.

(ix) It is important to realize that *hydrostatic* blood pressures increase *immediately* with the onset of "G", but that the protective reflexes (carotid sinus, etc.) require about 6 seconds to become effective. And also that shifts in blood volume, from the upper to the lower parts of the body, with decreased cardiac output, require several seconds for the effects to be significant.

(x) *"Blackout"* (complete loss of vision) is experienced on the average $+3.5\text{-}4.0G_z$ before loss of consciousness, because of the *intraocular pressure*, which is about 20 mmHg.

(a) When the arterial pressure at eye level falls to the order of 20-30 mmHg, the circulation to the eye is impaired or is stopped completely by this intraocular counter-pressure, although the cerebral circulation is still adequate.

(b) Because of the anatomy of the retinal circulation, the peripheral vision fails first. On artery enters the central portion of the retina and branches out to the periphery. Peripheral blood flow is the first to fail.

3. *The Effects of* $-G_z$ *Acceleration (Negative G)*

(a) The physiologically important forces act in a *headward* direction.

(b) Again, the effects on the *circulation* are the main considerations.

(c) The tolerance to negative G, when acting for several seconds, is probably not more than $-3G_z$ for the unprotected individual, and for most practical purposes, tolerance is $-2.5G_z$.

(d) *Subjective Symptoms during Footward Acceleration*

$-1G_z$: Same as standing on your head.

$-2G_z$: Gritty sensation in eyeballs. Pressure in the head. Disagreeable congestion in the soft tissues of the face and neck.

$-3G_z$: Eyeballs seem to be popping out. Skull feels as though it were expanding. Severe, throbbing headache, may persist for hours afterwards. Mental confusion may occur.

More than $-3G_z$: Usually intolerable for any length of time (several seconds).

(e) The subjective symptoms, as well as the objective findings, are greatly determined by duration of exposure to $-G_z$.

(i) Parachute opening in head down position may produce $-10G_z$ for 0.1 second without difficulty.

(ii) Downward ejection seat produces a negative acceleration of -7 to $-8G_z$ in 0.2 second and is well tolerated.

(f) *Objective Effects of Prolonged Footward Acceleration*

(i) With the onset of $-G_z$, blood pressure above heart immediately rises (both arterial and venous pressures). Cerebral spinal fluid pressure increases with the venous pressure.

(ii) If the acceleration is prolonged for more than a few seconds, the initially high arterial pressure tends to decrease towards the somewhat lower venous pressure as the heart slows and the cardiac output decreases. On the other hand, the venous pressure tends to slowly *increase* as blood is forced upward from the lower part of the body. Thus, the cerebral arterial and venous pressures tend to approach each other and the cerebral blood flow becomes slower and slower.

(iii) Decreased heart rate (carotid sinus reflex) is an effort to decrease the cardiac output and lower cerebral blood pressure. Asystole may occur and heart block may become imminent.

(iv) Drainage of blood from lower part of body toward the head, with decreased blood pressure below heart.

(v) All soft tissues of face and neck become engorged with blood and may become edematous if exposure is long enough. Lungs and thorax engorged with blood

(vi) The conjunctiva of the eyes are particularly sensitive to blood engorgement and small hemorrhages may occur over the surface of the eyeball.

(vii) Cerebral hemorrhages *within* the bony skull-case do *not* occur, because cerebral spinal fluid pressure, surrounding the cerebral blood vessels, also increases proportionately and prevents capillary rupture.

(viii) Respiration depressed. Due to upward weight of viscera against diaphragm.

(xiv) The so-called "redout" from $-G_z$ has never been observed experimentally. The early reports of redout described by pilots, on occasion, have been difficult to explain physiologically. Best explanation, probably, is that the engorged lower eyelid is forced up over eye and with light in the eyes would give the sensation of seeing red. The lower eyelid has no muscles for retarding the lid, since normally it is always in the down position. "Redout" is *not* caused by retinal hemorrhage. A true retinal hemorrhage causes complete loss of vision.

4. *Transverse Accelerations*

(a) $+G_x$ Acceleration (Forward Transverse)

When the inertial or centrifugal force acts perpendicular to the long axis of the body, the circulation and its hydrostatic pressures are not particularly affected. Thus, the usual symptoms noted in $+G_z$ acceleration do not occur in $+G_x$ acceleration unless the head and upper thorax are tilted forward into the G field creating a small but increasingly important $+G_z$ component. Usual subjective and objective symptoms are as follows:

(i) Chest pain is consistently noted above $+5G_x$. It is an intense, dull ache, generally more severe over the lower third of the sternum and in the epigastrum, frequently radiating along the costal margins, and usually more severe during inspiration.

(ii) Dizziness, vertigo, nausea, nystagmus, occur during post exposure period. A quick movement of the head will reinforce the vertigo for periods of up to 24 hours in some subjects exposed to severe $+G_x$ accelerations.

(iii) Only wrist and finger movements above $+8G_x$.

(iv) Difficulty in breathing.

(v) Decreased arterial O_2 saturation.

(vi) Increased respiratory frequency.

(vii) Decreased tidal volume.

(viii) Decreased vital capacity.

(ix) Slight increase in minute volume (due primarily to three-fold increase in respiratory frequency).

(x) Increased O_2 consumption due to increased work of breathing.

(xi) Blackout above $+7G_x$ if back angle is tilted forward 20-25°. Moving this angle to 10° reduces the blackout occurrence up to $+16.5G_x$: however, vision becomes blurred at this level. This blurring may be due to (1) interference of the optical property of the cornea by tears, or (2) eyeball distortion due to high G loading.

(xii) Coughing during the post-exposure period.

(xiii) Possibility of transient atelectasis due to dependent pulmonary pooling of blood and reduced blood flow.

(xiv) Petechial hemorrhage in unsupported regions of the posterior surface of the body.

(xv) Up to a short time ago (November 1964), no EKG abnormalities were noted in subjects exposed to accelerations up to $+16.5G_x$. However, recently, in highly motivated and physically qualified young men, some transient atrial and ventricular arrhythmias occurred in accelerations above $+8G_x$. Another series of runs by Russian investigators conducted at $+16G_x$, $+22G_x$ (50 seconds) and $+26.5G_x$ (3 seconds), showed fainting in some subjects between $+14\text{-}16G_x$. Also, they noted breaks in cardiac rhythm in the form of extra-systoles of various origins and sinus arrhythmias.

(b) $-G_x$ Acceleration (Backward Transverse)

(i) Subject seated upright - In this position, the inertial force is acting back-to-chest, tending to throw the pilot out of his seat. It is imperative that maximum restraint be effected at head, shoulders, chest, abdomen and hips, knees and ankles. Limiting factor appears to be severe pain in lower extremities, particularly if the legs are not restrained. Using maximum restraint, one series of centrifuge runs established the following tolerance:

$+4G_x$ – 3.5 minutes

$+8G_x$ – 0.5 minutes

$+12G_x$ – 3.6 seconds

(ii) Subject prone or semi-prone - At higher levels, the symptoms are pooling of blood in knees, petechial hemorrhages in dependent parts of the body, sagging lower eye lid, vertigo and dizziness in the post-run period, difficulty in breathing, nasal drip and mouth watering. Again, in one series of centrifuge runs, the following G vs. time tolerance limits were established:

$+3G_x$ - 15 minutes
$+4G_x$ - 3 minutes
$+5G_x$ - 5 minutes
$+6G_x$ - 4 minutes
$+8G_x$ - 2 minutes
$+10G_x$ - 2 minutes
$+12G_x$ - 30 seconds

It should be noted that in most instances, the above G-times are experimental limits and not subject limits.

2.4 Factors that Decrease Man's Tolerance to $+G_z$ Stress

1. Varicose veins.
2. Umbilical or inguinal hernia.
3. Hemorrhoids.
4. Eye disorders (i.e. glaucoma).
5. Any prostrating type of illness, flu, dysentery, etc.
6. Hypoglycemia - eat before flying.
7. Hypoxia
8. Chronic low blood pressure.

2.5 Factors that Increase Tolerance to $+G_z$ Stress

1. Tensing muscles (abdominal and leg muscles).
2. Modified valsalva maneuver (keep glottis open).
3. Yelling or grunting.
4. Fear (increases heart rate and raises blood pressure).
5. Excitement, apprehension, etc.
6. Hypertension.
7. Short, stocky individual does better.

3. PROTECTION AGAINST THE EFFECTS OF ACCELERATION

3.1 Chief Methods of Protection Against G Forces

1. Take advantage of physiological factors.
2. Change direction of body to a transverse position.
3. Special equipment to be worn by the aviator to increase G tolerance.

3.2 Physiological Factors Influencing G Tolerance

1. Voluntarily or involuntarily maintaining or increasing the blood pressure at the onset of acceleration.

(a) Tensing of muscles.

(b) Fear, anxiety, excitement, etc.

2. Good health and general physical condition are of importance.

(a) Avoid fatigue, sunburn, hypoxia, etc.

(b) Recent illness will tend to decrease G tolerance.

3. *The M-1 Maneuver:* While undergoing positive G, pull head and neck down between shoulders. Tense muscles of trunk and limbs. Keep on breathing, yell or grunt if necessary to *keep glottis open*. Keep maneuver up until force ceases. This maneuver is capable of increasing G tolerance by about 2G. However, it is fatiguing, particularly with repeated exposures to positive G.

3.3 Transfer of Direction of Accelerative Force to a More Nearly Transverse Direction

1. Crouching forward.

(a) Shortens hydrostatic blood column from heart to brain.

(b) Hard on the neck and back.

(c) Difficult to use gunsights, scan sky, etc.

2. High rudder bars tried by British and Germans, but this is quite awkward, especially during normal flight.

3. Tilting seat mechanism.

(a) Must tilt back 90^{o} during acceleration to be of real value.

(b) Problem of moving control instruments in this position is almost prohibitive.

4. Actual change in pilot position

(a) The Air Force has experimented with prone position for jet flight. NASA uses the semi-supine position for exit and re-entry in Mercury, Gemini, and Apollo.

(b) Will allow reduction in diameter of fuselage and better streamlining of plane.

(c) Position must be essentially horizontal before appreciable increase in tolerance occurs.

(d) In aircraft, technical problems are great, e.g., what to do with instrument panel; location of controls; support of head; scanning of sky; and escape from plane in this position.

(e) When horizontal position is used, rapid acceleration or deceleration of the plane will be exerted along the long axis of the pilot's body (i.e., $+G_z$ and $-G_z$ during take-offs and landings).

(i) It has been shown that when a human is in the horizontal position, tolerance for longitudinal G forces is decreased. Blackout may occur in a prolonged headward acceleration of $+2.2G_z$ when subject is in horizontal position.

(f) Proper restraint and protection during crash landings difficult to afford in horizontal position.

3.4 Special Anti-G Equipment for Protection Against $+G_z$

1. All equipment used in an attempt to support the circulation against the effects of G.

2. An abdominal belt fitted fairly tight was first tried. Fails because whole lower body needs support - not just the abdomen.

3. Taping of lower 1/3 to 1/2 of body. Used by Japanese. Protection of 0.3 to 0.8G can be obtained.

4. Frank's Flying Suit - developed by the RCAF in World War II. Consisted of an enclosed water jacket about the trunk and limbs. During an acceleration, the water increases in weight as does the blood. Thus a counter-pressure is developed over the outside of the lower body that is exactly equal to and counter-balances, the increased hydrostatic blood pressure. This was the first anti-G suit used in combat. Gave about 2.5G protection.

5. Pulsatile Pressure Suit - this was developed by the USN in 1941 and was designed to "milk" the blood toward the heart. Complexities involved discouraged its further use.

6. Pneumatic pressure-gradient suit by the USN, received flight tests in 1942. Used by USAF in 1943. Used 17 different rubber bladders. Gave about 1.6G protection against blackout.

7. The present standard anti-G suit (CSU/3P) is a cutaway model developed from earlier G-2 and G-3A suits. The five interconnecting bladders are equally pressurized during positive G and exert counter-pressure on the abdomen, thighs, and calves. The bladder pressure is metered by a "G valve"; the greater the G, the greater the pressure. This counter-pressure is exerted on the lower parts of the body during positive G.

(a) Reduces arterial blood flow to the lower limbs.

(b) Reduces the pooling of blood in the lower body by reducing blood volume below heart and aiding venous return.

(c) Abdominal counter-pressure prevents blood pooling and supports the diaphragm and heart from being displaced downward.

This suit (CSU/3P) gives about 2G protection. Will increase the tolerance to blackout from 4G to about 6G. The anit-G suit plus the M-1 maneuver gives about 3G protection.

High performance jet fighters are stressed to withstand about $10.5+G_z$. The anti-G suit is the best attempt so far to match the performance of the pilot to his plane.

3.5 Protection Against $-G_z$ Acceleration (Negative G)

1. As yet, there is no standard method or equipment for protection against $-G_z$ that is in use at the present time.

(a) The unprotected individual cannot tolerate much more than $-2.5G_z$ during a prolonged negative acceleration.

2. Experimentally, on the human centrifuge it has been shown that considerable protection against $-G_z$ is afforded by the pressure helmet.

(a) When the helmet is pressurized during negative accelerations, and the glottis is kept closed so that the lungs and thorax are not pressurized, negative G tolerance is doubled to -5G.

(b) This counter-pressure protects the eyes and the soft tissues of the face and neck from excessive engorgement and hemorrhage.

3. High performance, late model fighter planes are being stressed to withstand $-3G_z$.

3.6 Protection Against Abrupt Accelerations of High Magnitude, During Crashes, etc.

1. Increase the *area* of the body over which the force is applied.

(a) Crash helmets.

(b) Seat belts and shoulder harness. Wide straps and belts distribute the force over a larger body area than do narrow straps.

(c) Backward seating. This has been strongly advocated by safety experts for a long time. A few British airliners are now being built with backward seating for passengers.

2. Increase the distance over which a deceleration occurs.

(a) A rigid cockpit seat behind a crumpling nose.

(b) If a passenger, sit as far back in the plane as possible, with a good seat belt.

(c) Allow the structure of the plane to absorb and dissipate to a great part of the kinetic energy during a crash.

4. ACCELERATIONS INVOLVED IN AERIAL ESCAPE FROM AIRCRAFT

4.1

As with acceleration problems in general, the escape problem has increased proportionately with the development of high performance aircraft.

4.2

Prior to World War II, it was believed that man could bail out solely by his own efforts.

4.3

Reasons for emergency ejection seats in high speed aircraft:

1. Acceleration - At 2G, aviator has great difficulty in moving (getting out of plane). At 3G, he is completely immobilized.

2. *Dynamic pressures* - Air pressure increases directly as the square of the aircraft velocity. Impossible for aviator to bail out at more than 300 mph without being swept back into the tail surfaces of the plane.

3. *Lack of Sufficient Time to Accomplish Escape Unaided*

(a) Difficult to climb out of modern cockpits with all of the necessary bailout and survival equipment (exposure clothing, oxygen equipment, parachute, su val pack, etc.)

(b) A small delay in escape may be fatal.

4.4

At the present time, the Air Force has four main types of catapult ejection seats.

1. M-1: Upward ejection - for jet fighter planes. About 15G for 0.2 second (65 inch catapult stroke).

2. M-2: Upward ejection - for indoctrination purposes. About 12G fcr 0.1 second

3. M-3: Upward ejection - for jet bombers (B-47, B-52) with high tails. About 18G for 0.3 second.

4. M-4: Downward ejection - for the bombardier in the nose section of jet bombers. About 8G for 0.1 second.

4.5

Ejection seats will be constructed with an automatic lap belt release and an automatic parachute-arming device which operate within a few seconds after ejection from the plane.

4.6

The ejection seat has proved itself to be completely effective in about 70% of the escapes in which it has been used. In most cases, it would have been impossible for the aviator to escape without the ejection seat. The majority of the fatalities have occurred when the ejection seat was used at altitudes below 2000 ft.

4.7

The problem of escape from aircraft traveling faster than Mach 1 (faster than the speed of sound) no doubt will require that the aviator be protected inside a capsule or "pod". The abrupt deceleration that occurs immediately following ejection, at this speed depending on the air density (altitude), may be in the order of 40-50G.

5. THE PROBLEM OF TUMBLING (HEAD OVER HEELS) FOLLOWING EMERGENCY ESCAPE FROM AIRCRAFT

5.1

Tumbling frequently occurs following emergency ejection from aircraft.

1. It may be as fast as 180 rpm.

2. It is caused by the ejection seat catapult - not windblast.

3. It may last for 3-5 seconds (longer at high altitudes).

4. The physiological effects are studied experimentally on a "spin table".

5.2 The Physiological Effects of Tumbling

1. The accelerative forces drive blood to the extremities, headward and footward simultaneously (+ and $-G_z$).

(a) Get peripheral pooling of blood at both extremes.

(b) Decreased venous return to the heart.

2. The excessively high blood pressures in the extremities may cause petechial hemorrhage (extra-cranial).

3. Threshold times for conjunctival hemorrhages are

(a) When center of rotation is about the heart: 10 seconds at 100 rpm.

(b) When center or rotation is about the iliac crest: 2 minutes at 50 rpm. 3 seconds at 90 rpm.

4. Ejection seat causes rotation about an axis through the abdomen.

5. There is peripheral edema and severe discomfort at these threshold exposures.

6. Mental faculties are not impaired.

7. Vertigo occurs during *change* of rotational velocity (angular acceleration).

5.3

Despite these adverse effects, these are four reasons why it is desirable *not* to eliminate tumbling entirely:

1. To eliminate tumbling means modification of the ejection seat in such a way as to make it weighty, complicated, and unwieldy.

2. With not tumbling, there is a certain amount of "negative lift" after ejection. Thus, a much larger explosive charge would be needed to clear the tail.

3. It is possible that tumbling may help reduce the effects of high decelerative forces to which the body is subjected by air density.

4. Tumbling helps the aviator to leave the seat when the lap belt is released.

PRINCIPLES OF BIODYNAMICS

As Applied

to

Manned Aerospace Flight

PROLONGED ACCELERATION: Linear and Radial

CHAPTER III

THE DYNAMICS OF ROTATION APPLIED TO CENTRIFUGES

by

R. E. VanPatten

THE DYNAMICS OF ROTATION APPLIED TO CENTRIFUGES

1. INTRODUCTION

The classic treatments of rotational physics usually found in engineering textbooks and in advanced texts on gyrodynamics are ordinarily quite rigorous in their mathematical treatment of the subject. This paper is intended to present the subject in such a manner, first, as to relieve physicians and medical officers of the labor required to gain a rigorous insight into the subject and, second, to strip away the non-essentials associated with the classic developments which are not pertinent to the work at hand.

To this end, the treatment used in this paper will be largely intuitive, extensively graphical and the use of mathematics beyond algebra will be studiously avoided.

2. DEFINITIONS

In order to begin this discussion, we must first define the terms associated with the subject as they are commonly used and misused.

2.1 Displacement

This is a word which has several different meanings in the argot of the engineer. In this discussion, the meaning of displacement is simply *movement through a distance or an angle*. Thus, we may properly speak of a displacement of so many inches, feet, centimeters, meters, degrees, radians and so on. Note that time, as in the expression "feet per second," "radians per second" does not appear when we are speaking of a displacement. *Translation* means displacement along a straight line or a curve. *Rotation* means displacement at a fixed distance about a fixed axis.

2.2 Velocity

Velocity is the time rate of change of displacement, either linear or angular. If we displace an object or a point through a distance of 10 meters in an elapsed time of 2 seconds then that body or point may be said to have a velocity of 5 meters per second. In short, velocity is distance divided by time. In rotation, if a body rotates about some axis one full revolution (360 degrees or 2π radians) in 1 second, its velocity may be appropriately stated as one revolution per second, or 360 degrees per second, or 2π radians per second.

2.3 Acceleration

Acceleration is the time rate of change of velocity. If an object is traveling at a velocity of 10 meters per second and is accelerated to a velocity of sixty meters per second, the change in velocity is obviously 50 meters per second. If this change

in velocity is accomplished in an elapsed time of two seconds, then the *acceleration* is 25 meters per second per second, commonly expressed as 25 meters per second squared (25 m/sec^2).

If V_0 = the initial velocity (m/sec)

V_i = the final velocity (m/sec)

t = elapsed time (sec)

then

$$\frac{V_i - V_0}{t} = \frac{m}{sec} \times \frac{1}{sec} = \frac{m}{sec^2}. \qquad (1)$$

If a rotating body with an angular velocity of π radians per second undergoes a change in velocity resulting in a final velocity of 3π radians/sec in an interval of 1 second then the angular acceleration is similarly 2π radians/sec^2.

2.4 Jerk

Jerk is the time rate of change of acceleration. To give this term an everyday significance, consider the following situation. Assume that you are driving a very powerful automobile and are stopped at a traffic light. The light changes and you accelerate from rest. Inertially you will be aware of the acceleration by its tendency to press you into the seat and by the tendency of your head to roll back. Now while you're accelerating at partial throttle, let's assume that you decide to "see what she'll do" and abruptly apply full throttle. The rate at which you are gaining speed will abruptly change and the kinesthetic sensations provided by the inertial reactions will announce this in a more pronounced pressure against your back and the tendency for your head to snap back. This is jerk as encountered in a homely example. The units of jerk are typically meters/sec^3 (meters/sec^2/sec) or radians/sec^3 in angular terms.

2.5 Scalar

A scalar quantity is one which is described only by its magnitude, for instance, 10 pounds, 50 feet, 100 meters per second, 15 kilograms, are all scalar quantities even though their physical dimensions (length, mass, time) are all different.

2.6 Vector

A vector quantity is one which is described by its magnitude and direction. A common vector quantity can be found in the daily weather report where winds are described as, for example, "winds to the northeast at 15 knots". The direction in which a vector is acting is known as its *sense*, in the example cited, the sense is northeast, the magnitude is, of course, 15 knots.

2.7 Radial

Refers to force, displacement, velocity, or acceleration along a radius of a circle. These quantities may be centrally or peripherally directed and are represented by vectors.

2.8 Tangential

Refers to force, displacement, velocity, or acceleration along a line perpendicular to a radius and lying in the same plane as the radius. These quantities are likewise represented by vectors.

2.9 Centrifugal

From the latin centri (center) plus fugere (to glee). Centrifugal force is therefore, in rotational physics, a force directed away from the center of rotation.

2.10 Centripetal

From the latin centri plus petere (to move toward). Centripetal force is therefore, in rotational physics, a force directed toward the center of rotation.

2.11 Radian

The radian is a dimensionless unit (as is the angular degree) of angular measure. If we recall that the circumference (C) of a circle is

$$C = 2\pi r \,, \tag{2}$$

where r = radius and $\pi = 3.1416$,

then it is apparent that

$$r = \frac{C}{2\pi} \,. \tag{3}$$

In other words, if a length equal to the radius of a given circle were to be laid off circumferentially about that circle, it would be found that 2π (6.28) such lengths would measure off the circumference. Since the circumference of a circle encloses 360° than 2π radians = 360°.

By division, it may be found that 1 radian is equal to 57.3 angular degrees. Since all of the equations of rotation involve the quantity π , sooner or later, the ability to express angular displacement, velocity, and acceleration in terms of radians, radians/second, radians/sec^2 simplifies the algebraic manipulations considerably. This convenience is the primary reason for the existence of the radian as a unit of angular measure.

3. DIMENSIONAL EQUIVALENCE AND CONVERSIONS

Though not uniquely germane to the topic of this paper, this section is included because of the frequent necessity of converting units and the grief which may be avoided by a precautionary paragraph or so.

In physics there are three fundamental dimensions; mass, length, and time. In dimensional analysis, such as the development of empirical equations for experimental data, all units of measure are converted to mass/length/time terms so that the equations may be checked for dimensional homogeneity in order to avoid equating apples to oranges. Any further discussion of dimensional analysis is outside the limited scope of this paper; however, an application of the principles of dimensional analysis can be used almost daily in the laboratory.

As an example, suppose that you wish to convert some quantity expressed in (X) ft lb/sec to metric units of cm gm/sec.

The conversion is carried out by successive multiplication by dimensional fractions which are the dimensional equivalent of multiplication by 1/1 as below:

$$(X)\ \frac{\text{ft lb}}{\text{sec}} \times \frac{12 \text{ in}}{1 \text{ ft}} \times \frac{2.54 \text{ cm}}{1 \text{ in.}} \times \frac{1 \text{ kg}}{2.2 \text{ lb}} \times \frac{1000 \text{ gm}}{1 \text{ kg}} \ . \tag{4}$$

Observe that dimensions are cancelled exactly as though they were fractions and we find that

$$(X)\ \frac{\text{ft lb}}{\text{sec}} = \frac{(X)(12)(2.54)(1000)}{2.2}\ \frac{\text{cm gm}}{\text{sec}} \ , \tag{5}$$

since all English *units* have been previously cancelled out.

This is an especially useful technique and if conscientiously applied will save much time which might otherwise be spent in climbing out of dimensional pitfalls. In working with equations, such as those involving work, pressure, flow, Reynolds numbers and such, it is especially instructive to use this technique on both sides of the "equals" sign to discover if liters per second are being equated to kilograms per square centimeter.

A final word on dimensional consistency. Since there are two categories of units, namely the so-called absolute units of physics and the engineering units, one occasionally finds a situation in which both sides of an equation are inconsistent but in which the inconsistency is difficult to see. In such cases, the matter is usually settled by dividing or multiplying one or the other sides by the acceleration of gravity expressed in appropriate units. To sum up: the only mistake as common as a misplaced decimal point is an inconsistent unit and, when in doubt, try dividing or multiplying by the acceleration of gravity.

4. THE MECHANICS OF ROTATION

4.1 Uniform Angular Motion

The trivial case in rotational mechanics is the one of uniform angular motion. Assume that the centrifuge has been started up and the main arm is rotating at some uniform rate which we shall call ω and which will be expressed in radians per second (angular velocity), see Figure 1(a).

If we consider a point inside the gondola at some instant at which its position is at point P we can represent the velocity of the point *at that instant* as a vector V_1 pointing in the direction of rotation and tangential to the radial line OP.

If we consider the same point at some later instant (point Q), we find that its velocity at that instant is represented by a vector V_2 equal in magnitude to V_1. (How do we know the magnitude is the same? Because we said so when we defined the angular motion of the arm as uniform.) This vector V_2 is also pointing in the

direction of rotation and is also tangential to a radial line OQ. The important point to notice here is that, even though vectors V_1 and V_2 are equal in magnitude and are identical in orientation to the radial lines OP and OQ, they are different in that they point in different directions. It is appropriate to recall now that Newton said that a body in motion along a line tends to continue along that line unless acted upon by some other force. Obviously there is such a force acting in this case, the question being what is it and where does it come from?

The answer can be obtained by manipulating the vectors V_1 and V_2. Since they are defined as equal, defining one defines the other. If C is the circumference (in meters) of the circular path traveled by the point, and N is the rotational velocity in revolutions per second then

$$V = C(ft) \times N\left(\frac{rev}{sec}\right) ; \tag{6}$$

but

$$C = 2\pi R \tag{7}$$

so

$$V = 2\pi RN \frac{M}{sec} . \tag{8}$$

However, the angular velocity ω expressed in radians per second is equal to $2\pi N$, i.e.

$$\omega = 2\pi N\left(\frac{radians}{sec}\right) . \tag{9}$$

(Both revolutions and radians are dimensionless quantities).

So

$$V = R\omega = V_1 = V_2 \frac{M}{sec} \tag{10}$$

We have agreed that some force is changing the direction of V_2 with respect to V_1 and we also recall that Newton said that force is equal to mass times acceleration. We know that none of the masses are changing (assuming that nothing falls off the arm) so acceleration must be taking place in order to cause the change in direction of the vector.

You will recall that early on we defined acceleration as a change in velocity with respect to time. If we evaluate $V_2 - V_1/\Delta t$ (where Δt represents a *very small* increment of time), we can find the rate of change of velocity $\Delta v/\Delta t$ and this will be the acceleration we are looking for. To avoid the use of the calculus, we will settle for the average acceleration over the time required for the gondola to move from P to Q.

Figure 1(b) is a graphical solution. We have taken a point halfway between P and Q. Maintaining original magnitudes and angles we have transferred vector V_1 to this point and, by reversing its sense, we have placed V_2 tail to nose with V_1 thus subtracting it from V_1. By completing the vector triangle we see that ΔV (the average change in velocity) is aligned with the radius and directed toward O. Now that we know this we can find out the magnitude of ΔV by an approximation.

Let us assume that the angle $\omega\Delta$ is very small so that (Fig. 1b) the difference between the chord ΔS and the arc PQ is so small as to be insignificant. Now, let us go back to Figure 1(b).

The triangle OPQ has two equal sides of length R . The triangle 123 has two equal sides $(V_1 = V_2)$. Accordingly these are both equilateral triangles. By referring to Figure 1(b), we see that side ΔV of triangle 123 is perpendicular to side ΔS of triangle OPQ and that indeed the other sides are also mutually perpendicular. This being the case, these two triangles are similar triangles and we can define the following relations:

$$\frac{\Delta V}{V} = \frac{\Delta S}{R} \tag{11}$$

$$\Delta V = V\frac{\Delta S}{R} \tag{12}$$

$$\frac{\Delta V}{\Delta t} = \frac{V}{R} \times \frac{\Delta S}{\Delta t} . \tag{13}$$

However, $\Delta S/\Delta t$ is a change in displacement divided by a change in time, which is by definition *velocity*, so

$$\frac{\Delta V}{\Delta t} = \frac{V}{R} \times V = \frac{V^2}{R}\left(\frac{ft}{sec^2}\right) \tag{14}$$

or in angular terms, since $V = 2\pi RN = R\omega$,

$$\frac{\Delta V}{\Delta t} = \frac{R^2\omega^2}{R} = R\omega^2\left(\frac{ft}{sec^2}\right) \tag{15}$$

We now see that $\Delta V/\Delta t$ is the operating acceleration in this case and, since it points in the direction of the center of rotation, we shall call this the centripetal acceleration. In the famous case of the bucket of water whirling at the end of a rope, the force which keeps the bucket moving in a circle (instead of flying off on a tangent) is the centripetal acceleration times its mass. The force which keeps the water in the bucket is - $R\omega^2$ times the mass and is called the centrifugal force, which neatly accounts for equilibrium according to the Newtonian assertion that for every force there is an equal and opposite reaction.

4.2 Nonuniform Angular Motion

As has just been shown, during uniform angular motion the total acceleration, neglecting the earth's gravitational vector, is the centripetal acceleration directed along a radial line. During nonuniform angular motion, for example in the case in which the centrifuge main arm is being accelerated from rest to some chosen rate of rotation, the magnitude and direction of the total acceleration vector is undergoing changes proportional to the rate of change of the main arm angular velocity.

Figure 2 graphically represents the situation which prevails during nonuniform angular motion. As the figure shows, the velocity V_1 at position (1) is not the same as velocity V_2 at position (2) because the arm is moving faster at (2) than it is at (1). Accordingly, when we use the vector subtraction method at a point midway between (1) and (2) we find that V_2-V_1 yields a resultant vector ΔV which is not directed centrally and which in addition changes both its magnitude and direction over the next time interval from (2) to (3). Here the situation is such that no little pleasantries such as similar equilateral triangles and making all angles small angles are going to help us much.

There is yet another problem to be faced, which has to do with the orientation of the acceleration vector with respect to the subject in the gondola. Obviously at the exact instant of start-up, all acceleration, for a split instant, is directed tangentially. As we have seen, when the arm reaches peak speed and settles down to a steady rate of rotation we are then in a uniform angular motion regime and the total acceleration vector will be all centripetal, directed inward radially. This means that, in the interval between starting and attainment of the desired plateau, the acceleration vector must swing through 90 degrees.

Now, were the subject seated in a fixed angular position at the end of the arm facing in the direction of rotation (tangentially) he would, at the instant of starting, feel the inertial response to acceleration as a force perpendicular to his chest in the chest-to-back direction. Were he to maintain this position, fixed angularly with respect to the arm, he would feel this force sweeping through an angle of 90 degrees about an axis through the top of his head and the seat of his pants. Finally at peak centrifuge arm rotation the magnitude of this force would stabilize and would be felt as a force acting on him from left to right. This is obviously a poor way to build a centrifuge and brings us to one of the reasons why centrifuges are often gimballed, so that they can be pivoted around the gondola axes.

We must arrive at some orderly way of describing the magnitude of total acceleration and angular position of the gondola with respect to the arm at any given instant. In the actual operation of a gimballed centrifuge, any given run will be characterized by an acceleration versus time profile. Figure 3 is an elementary example (showing only the onset portion of the profile). This plot calls for the total acceleration to increase in a linear manner (neglecting earth's gravity) from zero to 10G in 10 seconds, an average onset of 1G per second.

This plot gives us the first piece of information we need, namely the magnitude of the total acceleration vector at every instant during the onset. It tells us nothing, however, about how fast the arm must be rotating at any given instant or though what angle the gondola must have been rotated in order to achieve vector alignment at any given time.

If we look again at Figure 3, it is apparent that at any time after start and before the uniform angular motion regime begins (plateau) the total acceleration vector can be resolved into two rectangular components, a centripetal component a_r and a tangential component a_t. Thus, the total acceleration vector (A) forms the hypotenuse of a right triangle having two sides equal to a_r and a_t, neither of which is necessarily equal to the other.

Now, by resorting to the Pythagorean Theorem we can say that

$$A = \sqrt{(a_r^2 + a_t^2)} \tag{16}$$

Since a_r is the centripetal component we know that

$$a_r = r\omega^2 . \tag{17}$$

If ω were constant the tangential *acceleration* component would be zero, since $\Delta\omega/\Delta t$ would be zero and the tangential *velocity* would be $r\omega$ as we have seen. In this case, however, $\Delta\omega/\Delta t$ is not zero but is changing so that $(\omega_n - \omega_{n-1})/t$ has some finite value at every instant (n). Accordingly the tangential acceleration is $r\Delta\omega/\Delta t$ or

$$\frac{r\omega_n}{\Delta t} - \frac{r\omega_{n-1}}{\Delta t} .$$

If we now substitute these expressions, we have

$$A = \sqrt{\left[(r\omega_n^2)^2 + \left(\frac{r\omega_n}{\Delta t} - \frac{r\omega_{n-1}}{\Delta t}\right)^2\right]} ; \tag{18}$$

if we let $t = 1$ second this simplifies to

$$A = \sqrt{[(r\omega_n^2)^2 + (r\omega_n - r\omega_{n-1})^2]} ; \tag{19}$$

expanding this

$$A = \sqrt{[r^2\omega_n^4 + r^2\omega_n^2 - 2r\omega_n\omega_{n-1} + r^2\omega_{n-1}^2]} . \tag{20}$$

Despite its appearance this expression is not as bad as it looks. Since we know the value of the total acceleration (A) at any instant from our G versus time profile, and since (r) the distance from the center of rotation to the center of the gondola is known and is fixed, we can then square both sides of this equation, plug in the numbers we know and solve the resulting quartic equation for the value of ω.

By virtue of some rather tedious arithmetic, this equation can be solved, and once ω is known then a_r and a_t can be calculated. If we call the angle through which the cab has been rotated Φ, since a_r and a_t form the opposite and adjacent sides of a right triangle of which Φ is an angle, then at any given time

$$\Phi = \arctan\left(\frac{a_r}{a_t}\right) . \tag{21}$$

Now we have all the information needed to write a computer program which could generate the commands resulting in machine performance in accordance with our desires.

4.3 The Coriolis Acceleration

Gaspard Gustave de Coriolis (1792-1843) was an observant gentleman who noticed that in rotating systems things are not always what they appear to be. The acceleration

named after M. de Coriolis is responsible for diverse problems involving the flight of ICBM's, long range artillery shells, the bearings in steamship turbines, and strangely disturbing vestibular effects in subjects in aircraft and in ground-based simulators.

This last item is of interest to us and it is therefore useful to try to give at least an intuitive grasp of what Coriolis effects are like. Consider the rotating disc of Figure 4 viewed from above and assumed to be rotating at a constant angular velocity ω. Over a time interval Δt an angle $\omega\Delta t$ will be swept out by any given radial line.

From earlier discussion, it has been agreed that the circumferential (tangential) velocity of any point is $R\omega$ and, if ω is constant, the velocity is dependent upon the distance R from the center of rotation. Obviously the distance ΔS_1 is less than ΔS_2 and the velocity $R\Delta S/\Delta T$, is less than the velocity $(R+\Delta R)\,\Delta S_2/\Delta T$. By following this argument a little further, it is apparent that every point on a radial line is moving at a different velocity.

If a particle were to be moved from (1) to (2) while the disc was rotating through $\omega\Delta t$ it is apparent that during this period of time the velocity of the particle would increase, since it is moving from a location with a velocity of $R\omega$ to a location with a velocity of $(R+\Delta R)\omega$. Since a change in velocity over time has been defined as acceleration, it is obvious that this particle is being accelerated. Likewise, if the particle were to move from (2) to (1), the acceleration would be the same but opposite in sign (deceleration). This effect is one manifestation of the Coriolis acceleration.

Through the use of one small deceit, an attempt will now be made to arrive at an expression which defines Coriolis acceleration in terms of angular velocity and the velocity with which the point of interest moves along a radial line.

To begin with, in Figure 5 we have a representation of a vector V_r rotating about a center 0, through an angle $\omega\Delta t$, the velocity at the tip of V_r being equal to $r\omega$. If this were a conventional triangle, then

$$\sin \omega\Delta t = \frac{r\omega}{V_r}; \tag{22}$$

but we would like to say that $\omega\Delta t$ is a very small angle and that we be allowed to assume that $\sin \omega\Delta t = \omega\Delta t$. If this be permitted then

$$\omega\Delta t = \frac{r\omega}{V_r} \tag{23}$$

and

$$r\omega = V_r\omega\Delta t. \tag{24}$$

Returning now to Figure 4 we can say that:

The change in velocity ΔV = original velocity at point (1)

\+ the new angular velocity obtained by moving from (1) to (2)

− the system velocity.

The original velocity at point (1) = $r\omega = V_r \omega \Delta t$ (see Equation (24))

The new angular velocity = $(r + \Delta r)\omega$

$= (r + V_r \Delta t)\omega$, because $\Delta r = V_r \Delta t$

The system velocity is simply $(r\omega)$, so

$$\Delta V = V_r \omega \Delta t + (r + V_r \Delta t)\omega - r\omega$$

$$= V_r \omega \Delta t + r\omega + V_r \omega \Delta t - r\omega$$

$$= 2V_r \omega \Delta t$$

and:
$$\frac{\Delta V}{\Delta t} = 2V_r \omega \text{ , which is the Coriolis acceleration .}$$

In effect, the Coriolis acceleration is twice the product of the angular velocity and the relative velocity of the particle *perpendicular* to the axis of rotation.

4.4 Some Examples of Coriolis Effects

So much for some of the mathematics of the Coriolis acceleration. What are the practical effects of this feature of rotational mechanics? Returning to Figure 4, suppose that you are seated directly above point 0 and facing outward along the line 0-1-2 with the platform rotating as shown. Suppose further that you are provided with an instrument panel, at a convenient reach distance, on which there are switches you must operate on occasion.

Imagine yourself seated quietly, hands in lap, rotating about the axis through 0 . Now try operating one of the switches. As you reach out, your hand is traveling along a radial line into a region of higher angular velocity and accordingly will be accelerated in the direction of rotation. To you surprise, you will find your fingers disobeying your instructions and contacting the panel to the left (inertial response) of the switch.

Conversely if you were to withdraw your hand from the panel and grasp the arm of your chair you would find yourself attempting to grasp a point to the right (inertial response) of the intended since your hand would be undergoing transition into a region of lower angular velocity and thus an acceleration of opposite sign.

Vertical motions in such a situation, provided they took place at a constant radial distance, would involve no Coriolis effects because such motions are in a direction parallel to the axis of rotation and, as we have seen, it is the velocity in a direction perpendicular to the axis of rotation which generates the Coriolis effects.

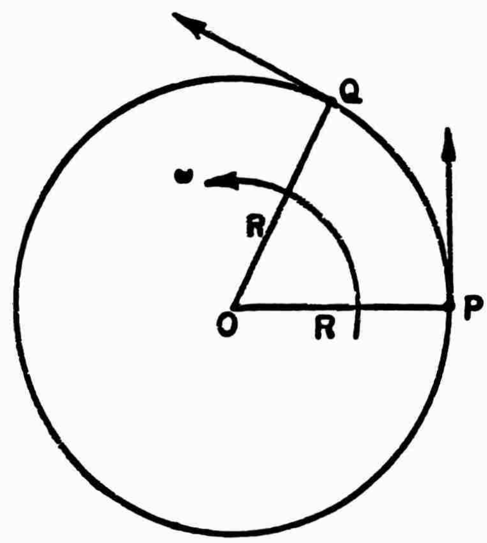


Fig. 1(a) Uniform angular motion

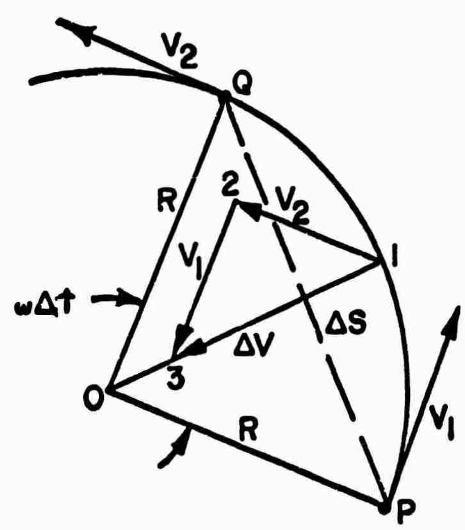


Fig. 1(b) Graphical solution - uniform angular motion

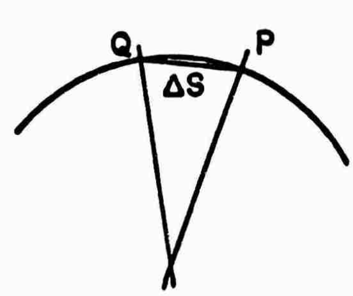


Fig. 1(c) Chordal distance

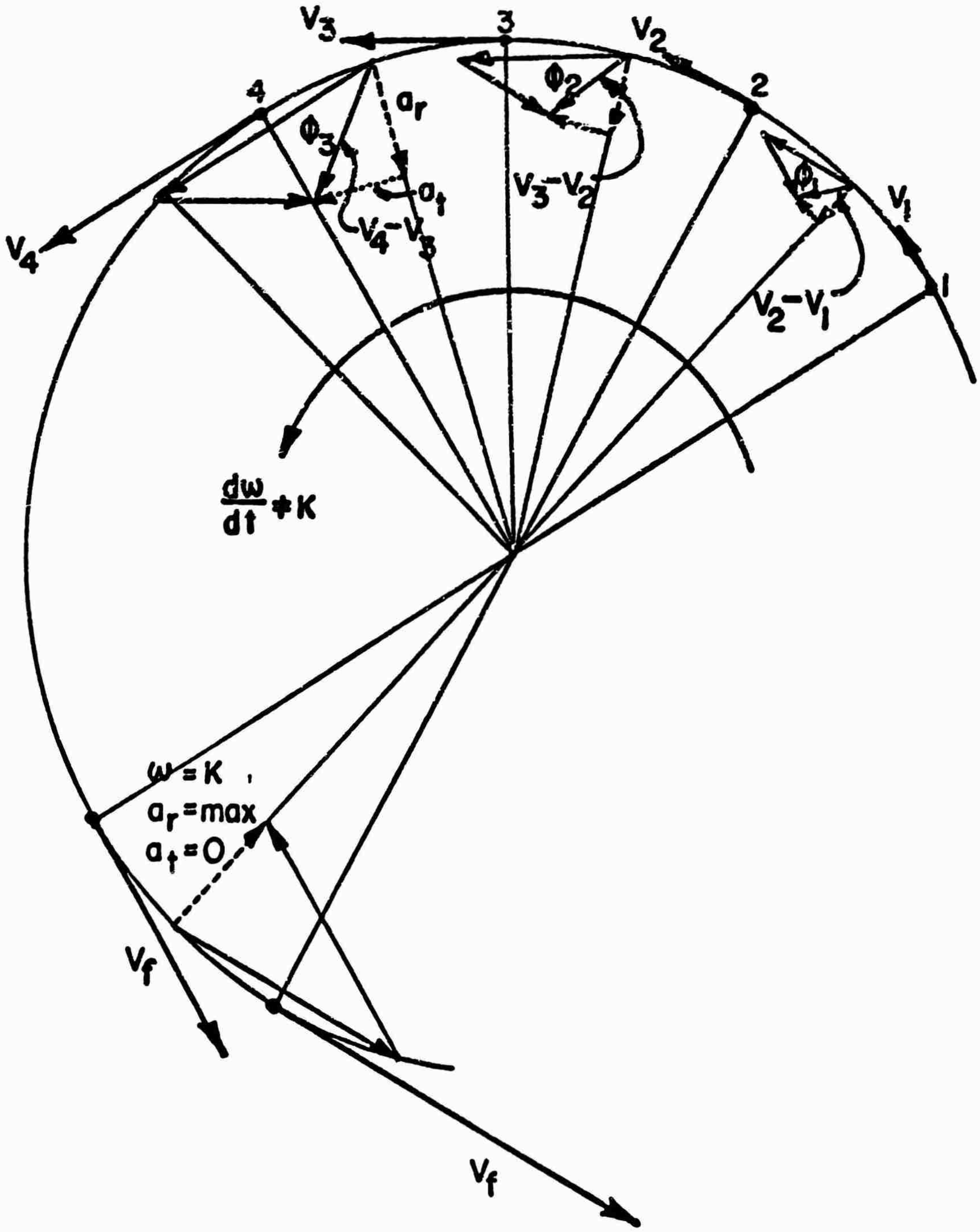


Fig. 2 Graphical solution - nonuniform angular motion

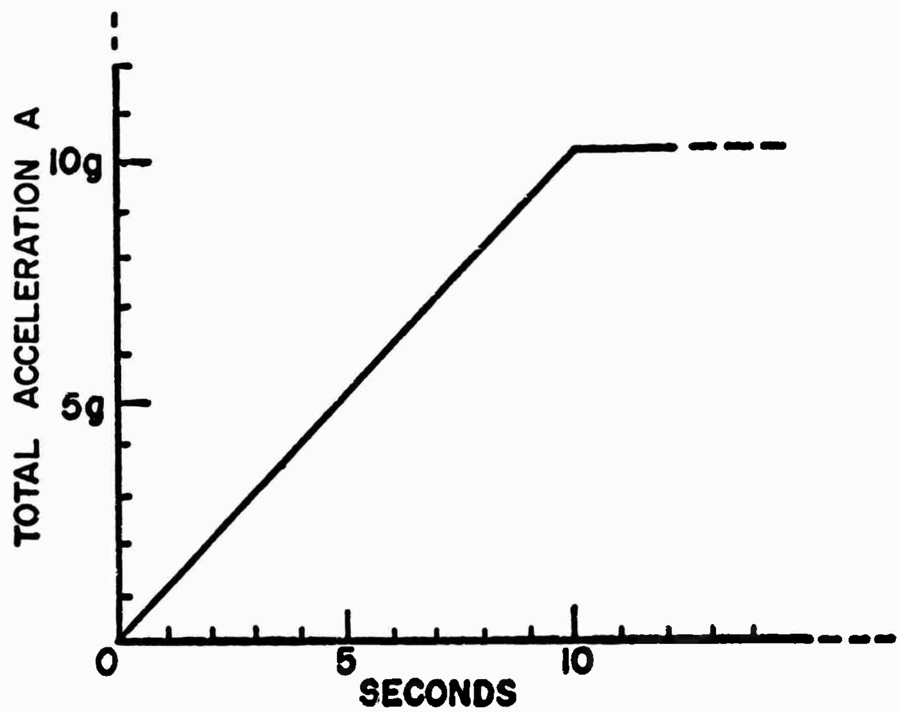


Fig. 3   Acceleration versus time profile example

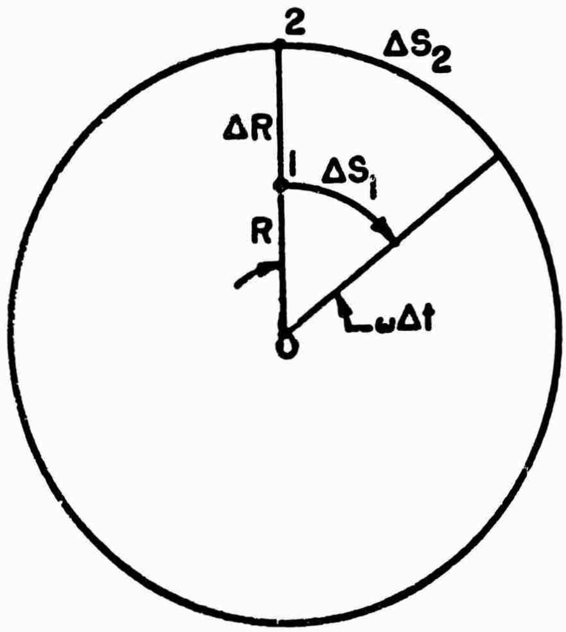


Fig. 4 Variation in velocity along a radial line

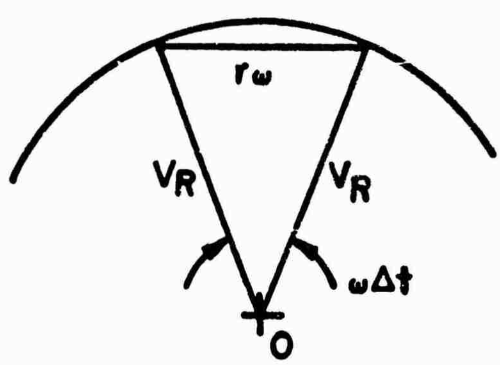


Fig. 5 Toward proof of Coriolis equation

PRINCIPLES OF BIODYNAMICS

As Applied

to

Manned Aerospace Flight

PROLONGED ACCELERATION: Linear and Radial

CHAPTER IV

A SUMMARY OF HUMAN TOLERANCE TO PROLONGED ACCELERATION

by

A.S.Hyde and H.W.Raab

A SUMMARY OF HUMAN TOLERANCE TO PROLONGED ACCELERATION

1. INTRODUCTION

For vehicle design and mission analysis, any clearly expressed relationship existing between man's tolerance and the onset rate, magnitude, and duration of sustained acceleration force would be desirable. Indeed, attempts have been made by some experimenters (e.g., Refs. 5, 16, 19) to express these relations. Their utility, however, is limited because they are inaccurate. This has been established by comparing the attempted predictions with data obtained from reviewing the literature reporting human acceleration tolerance experiments. Such inspection demonstrates nearly random disparity between prediction and reality, with both over- and under-estimation of tolerance occurring often and with random severity.

We have no quarrel with the desirability of establishing stimulus/response relationships; they are a major goal of environmental physiologists and a continuing need for design engineers. Because no predictive relationship has yet been found, this report presents a summary of data from the literature in the form of tables and graphs, using standard terminology.

2. ACCELERATION TERMINOLOGY

Table I summarizes the terminology in use in major laboratories throughout the world; it is derived from an AGARD - NATO agreement regarding the equivalence of acceleration terminology. The terms in this report are those of Table B, System 4, entitled: Physiological Computer Standard. This system is preferred by facilities with multiple degree-of-freedom devices on the basis of simplifying computer programing. This system of terminology utilizes *the direction in which tissue is displaced* as a result of acceleration, either angular or linear.

3. METHOD OF PRESENTATION

Most of the graphs present the magnitude of acceleration on an arithmetic ordinate axis and the duration of exposure on a logarithmic abscissa. Separate groups of graphs are included for each direction of acceleration, i.e., the X, Y, and Z (orthogonal) axes. Each group of graphs (G_x , G_y , G_z) is further divided on the basis of the presence, absence, or character of experimental variables, such as restraint and support system, aides (i.e., anti-G suit, pressure breathing, etc.) and the number of subjects involved ($n = 1$, $n > 1$) .

For each graphic summary of magnitude, direction, and duration, a stick-figure illustration of the subject's attitude is given (with respect to the acceleration vector) and a table is provided. Each table defines each point on each graph with respect to the following variables: vector magnitude, duration, average onset (G/second), back angle (degrees of tilt), cause of termination of experimental exposure, trauma, number of subjects involved, countermeasures used, support, restraint, and the reference from which this information was obtained.

4. RESULTANT VECTOR MAGNITUDES AND THE RETINAL-AORTIC AXIS

The $+G_z$ (footward inertia) component of any acceleration directly influences a subject's tolerance to any acceleration. The footward redistribution of blood produced by this direction of inertial force first influences the perfusion of blood to the subject's eyes, through his brain, causing loss of vision (blackout), and loss of consciousness, respectively.

An important, but obscure, relation exists between the anatomic $+G_z$ and the physiologic $+G_z$, the latter being termed Retinal-Aortic $+G_z$. This relation results because the eyeballs are in front of (ventral to) the anatomic G_z axis. That is, a line drawn from the root of the heart to the eyes and a line extended along the G_z axis and passing through the heart will include an angle of approximately 15°. In Figure 1, the effective angle causing blackout, termed the Retinal-Aortic $+G_z$, is compared to the $+G_x$ and $+G_z$ component of any given acceleration. The ordinate in Figure 1 gives the percent of any acceleration vector amplitude in each of three axes ($+G_z$, $+G_x$, and Retinal-Aortic $+G$), all as a function of the back angle (the amount of forward angulation of the subject toward the direction of acceleration). The angle included between the subject's $+G_z$ axis and the plane normal (perpendicular) to the direction of acceleration is given as the abscissa. For example, if a subject is inclined 45° toward a 10G acceleration, the acceleration is then termed either a $+10G_x$ or a $+10G_z$, and the resultant in the X-axis (see Figure 1) is about $+7G_x$ and the apparent $+G_z$ acceleration is also $+7G_z$. However, the Retinal-Aortic $+G_z$ is 15° forward and the effective vector component contribution to blackout, therefore, is about $+9G_z$. With regard to causing blackout, this is approximately 28% greater than is apparent from the $+G_z$ component used alone.

The reader must be sensitive to the back angles utilized in $+G_x$ acceleration. Resolving the $+G_z$ component of a $+G_x$ acceleration is not enough; the reader must also resolve the Retinal-Aortic axis component if he desires to realize the effective contributor to blackout or loss of consciousness evolving from a given $+G_x$ acceleration. The same applies to $+G_z$ accelerations; the reader must again obtain the Retinal-Aortic component to predict probable tolerance in the Z-axis.

5. TOLERANCE

The term "tolerance" means different things to different people. The flight-controls designer designates a given decrement in man-machine performance as unacceptable, and any environmental input that causes less than this given decrement is termed "tolerable". The physiologist designates certain functional decrements, say a 30% decrease in cardiac

output, as "intolerable". The same may be true of other reference systems, such as visual acuity; thus, the particular tolerance that is meant must be defined.

In this report the term "tolerance" also means many different things, because the various investigations reported herein were often of different intent; therefore, different criteria were used for what was and was not tolerable. The criteria used to terminate any given experiment have been assigned to categories (in this report) as "subjective" or "arbitrary" (time limit). The reader should consult the specific report referenced for details of any given point on the graphs.

To reduce the number of points plotted on the graphs, only the highest runs (both amplitude and duration) of any series were used. Replication of magnitude points of different durations of exposure indicates that other significant variables should be considered, since large differences in tolerance were obtained with different restraint systems, countermeasures, and so forth. The graphs and tables (Figs. 2-14 and Tables II-XIII) necessarily represent present upper limits of known, primarily subjective, tolerance, and should be recognized as upper limits; there are many subjects who, for any given time, duration, and direction of acceleration, could not tolerate the exposure.

6. SUMMARY OF DATA: EXPLANATION OF TERMS AND COLUMN HEADINGS

G (Dimensionless):
The ratio of acceleration (deceleration) resulting from a change in velocity or direction to acceleration due to the earth's gravity.

Resultant Vector Magnitude (G):
The resultant inertial force (in G units) acting on a subject resolved from component forces, such as tangential, centripetal, linear, and gravitational acceleration.

Component Vector(s) Magnitude (G):
The orthogonal component(s) of the resultant vector.

Vector Magnitude (G):
Same as resultant vector magnitude.

Duration at G (Seconds):
The length of time a subject is at the G-level indicated. "Peak" denotes an acceleration profile with no "plateau". At the rates of onset in this report there is little error in plotting "peak" as equivalent to a one-second duration.

Average Rate of Onset (G/Second):
A measure of how rapidly G is applied to the subject.

Back Angle (Degrees):
The angulation of subject's trunk with respect to a plane normal (perpendicular) to the resultant acceleration axis. (See the "Subject Configuration" figures.)

Cause of Termination:

The symbol (S) is used when the subject terminates the experiment because of pain, fatigue or dyspnea, or when he is not permitted to continue because of heart rate, ECG changes or "blackout."

The symbol (A) is used for termination of totally arbitrary nature, such as arbitrary time limits, or completion of experimental measurements.

Trauma:

Trauma listed are those reported in the references and are of a "serious" nature. The notation "none" does not exclude "blackout," petechiae, fatigue or discomfort.

Number of Subjects Attaining:

A duration attained by a single subject (n = 1) in a group of subjects (e.g., 1 of 4) is the longest of the group. Durations attained by more than one subject (n > 1) in a group of subjects (e.g., 3 of 4) are the longer of the group.

Countermeasures:

Countermeasures are those aids (e.g., Anti-G suit) which are intended to augment the physiology of the subject. The notation "none" does not exclude the use of "natural" aids, such as straining (M-1 maneuver) and abdominal breathing.

Support:

A structure, such as an aircraft seat, that supports a subject's body and determines the presentation of the subject to the inertial vector.

Restraint:

Restraints are those accessories (e.g., harness) that restrain the subject from forces that the support does not.

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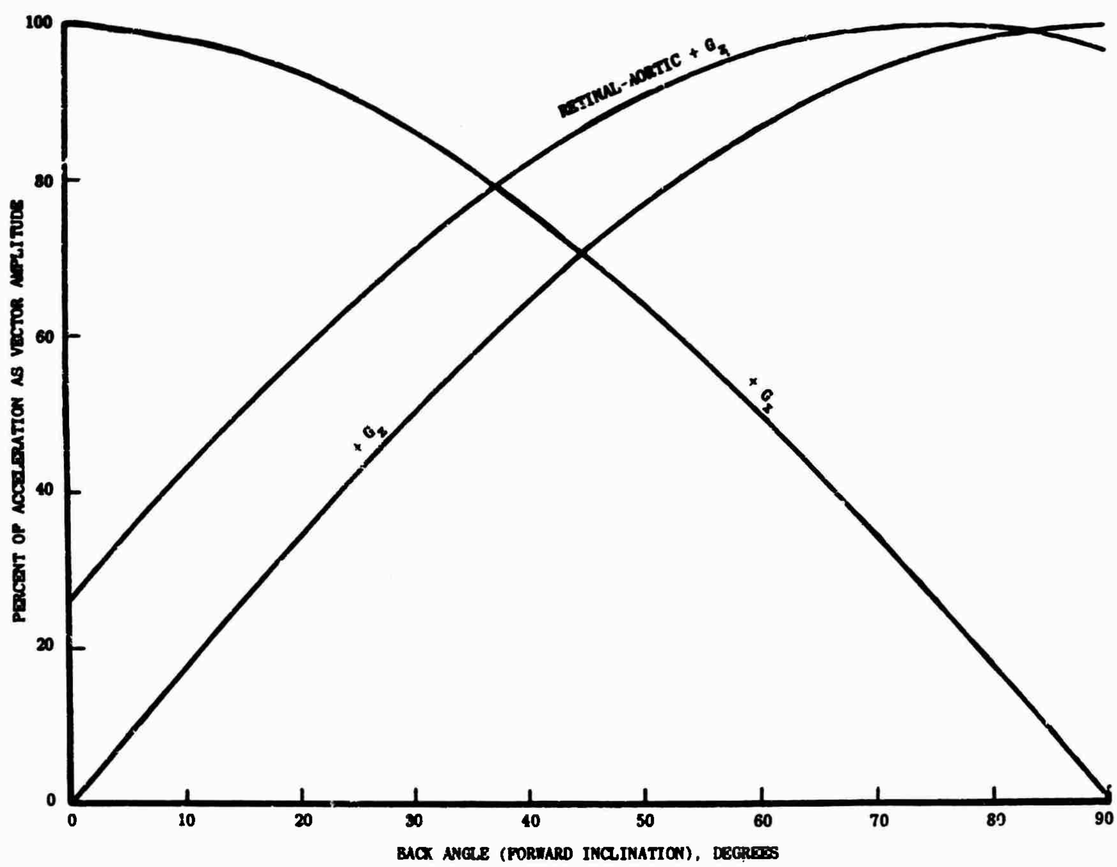
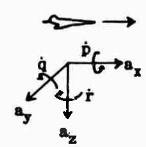


Fig. 1 Resolution of important vectors of any given X-, or Z-axis accelerations (Ref. 18)

TABLE I

Body acceleration - Comparative table of equivalents (Ref. 12)



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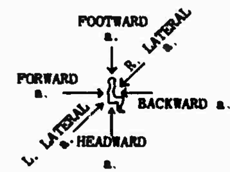

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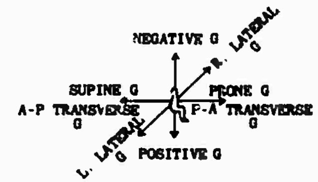

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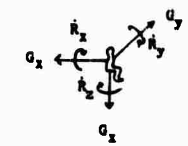


SYSTEM 4

LINEAR MOTION	TABLE A Direction of Acceleration		TABLE B Inertial Resultant of Body Acceleration		
	Aircraft Computer Standard (Sys. 1)	Acceleration Descriptive (Sys. 2)	Physiological Descriptive (Sys. 3)	Physiological Computer Standard (Sys. 4)	Vernacular Descriptive
Forward	$+ a_x$	Forward accel.	(1. 2) Transverse A-P G Supine G Chest to Back G	$+ G_x$	Eye Balls In
Backward	$- a_x$	Backward accel.	Transverse P-A G Prone G Back to Chest G	$- G_x$	Eye Balls Out
Upward	$- a_z$	Headward accel.	Positive G	$+ G_z$	Eye Balls Down
Downward	$+ a_z$	Footward accel.	Negative G	$- G_z$	Eye Balls Up
To Right	$+ a_y$	R. Lateral accel.	Left Lateral G	$+ G_y$	Eye Balls Left
To Left	$- a_y$	L. Lateral accel.	Right Lateral G	$- G_y$	Eye Balls Right
ANGULAR MOTION					
Roll Right	$+ \dot{p}$		Roll	$- \dot{R}_x$	
Roll Left	$- \dot{p}$			$+ \dot{R}_x$	
Pitch Up	$+ \dot{q}$		Pitch	$- \dot{R}_y$	
Pitch Down	$- \dot{q}$			$+ \dot{R}_y$	
Yaw Right	$+ \dot{r}$		Yaw	$+ \dot{R}_z$	
Yaw Left	$- \dot{r}$			$- \dot{R}_z$	

FOOTNOTES:

1. Large letter, G, used as unit to express inertial resultant to whole body acceleration in multiples of the magnitude of the acceleration of gravity. Acceleration of gravity, $g_0 = 980.635$ cm/sec^2 or 32.1739 ft/sec^2.
2. A-P, P-A refers to Anterior-Posterior, Posterior-Anterior.

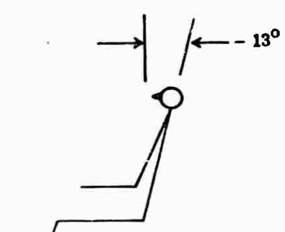
TABLE II

$+G_z$ n = 1

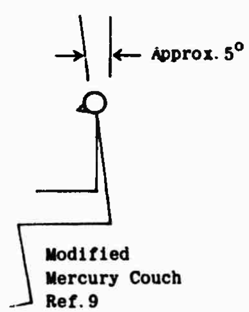
Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures		Support	Restraint	Reference
					Unaided n = 1						
4.5	660	0.07	-13°	A	None	1 of 8	Subjects Instructed to Relax	None	Aircraft Seat	Integrated Harness	20
4.0	1260	0.07	-13°	A	None	1 of 8		None	" "	" "	20
3.5	3600	0.07	-13°	A	None	1 of 8		None	" "	" "	20
					Aided n = 1						
16.0	Peak	12.5 Sec. to Peak Sinusoidally	Approx. 0°	S	Irritation of Glottis and Pharynx	1	Hydrostatic Counter-pressure to Eye Level		"Mayo Tank"	Bungee Cords	15
6.0	390	?	Approx. 5°	S	None	1	Anti-G Suit		Modified Mercury Couch	Helmet and Webbing	9
6.0	120	0.07	-13°	A	None	1 of 8	" " "		Aircraft Seat	Integrated Harness	20
5.0	300	0.07	-13°	A	None	1 of 8	" " "		" "	" "	20
4.0	1200	0.07	-13°	A	None	1 of 2	" " "		" "	" "	20
3.5	3600	0.07	-13°	A	None	1 of 4	" " "		" "	" "	20

* See also Figure 15 for tolerance levels using the criterion of vision.

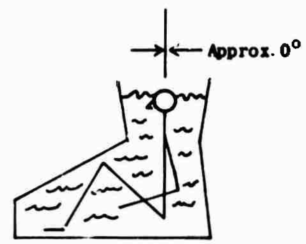
Subject Configuration



A/c Seat
Ref. 20



Modified
Mercury Couch
Ref. 9



"Mayo Tank"
Water Immersion to
Eye Level Ref. 15

Inertial Force

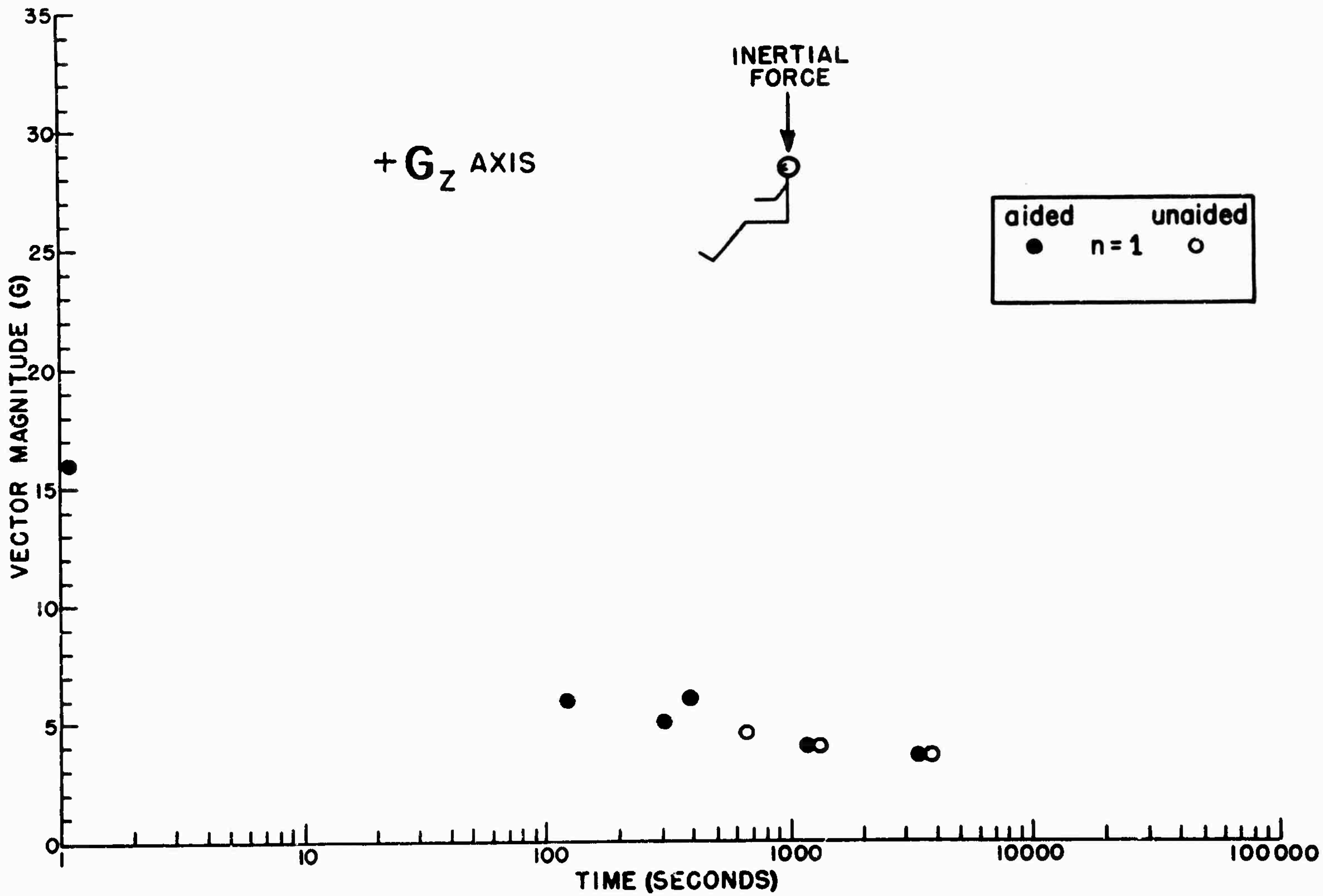
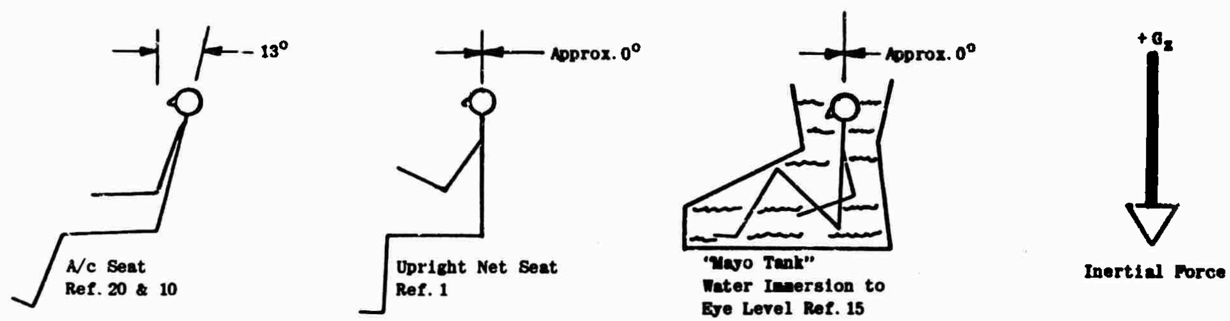


Fig. 2 Prolonged acceleration tolerance

TABLE III

$+G_z$ n > 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
					Unaided n>1					
9.0	Peak	0.07	0°	A	None	2 of 31	None (M-1 Maneuvers)	Upright Net Seat	None	1
7.0	15-30	0.56	Approx. −10°	A	None	3 of 33	None	Aircraft Seat	?	10
5.0	240	0.07	−13°	A	None	3 of 8	Subjects Instructed to Relax None	" "	Integrated Harness	20
4.5	≥540	0.07	−13°	S	None	3 of 8	None	" "	" "	20
4.0	≥1200	0.07	−13°	A	None	3 of 8	None	" "	" "	20
3.5	>2700	0.07	−13°	S	None	3 of 8	None	" "	" "	20
3.0	3600	0.07	−13°	A	None	7 of 8	None	" "	" "	20
					Aided n>1					
10.5	Peak	12.5 Sec. to Peak Sinusoidally	Approx. 0°	A	None	2	Hydrostatic Counter-pressure to Eye Level	"Mayo Tank"	Bungee Cords	15
10.0	Peak	12.5 Sec. to Peak Sinusoidally	Approx. 0°	A	None	3 of 3	" " " "	" "	" "	15
7.0	15-30	0.56	Approx. −10°	A	None	13 of 30	Anti-G Suit	Aircraft Seat	?	10
6.0	≥60	0.07	−13°	S	None	4 of 8	" " "	" "	Integrated Harness	20
5.0	≥240	0.07	−13°	A	None	6 of 8	" " "	" "	" "	20
4.5	600	0.07	−13°	A	None	4 of 8	" " "	" "	" "	20
4.0	≥720	0.07	−13°	S	None	2 of 2	" " "	" "	" "	20
3.5	≥1340	0.07	−13°	S	None	4 of 4	" " "	" "	" "	20
3.0	3600	0.07	−13°	A	None	2 of 3	" " "	" "	" "	20



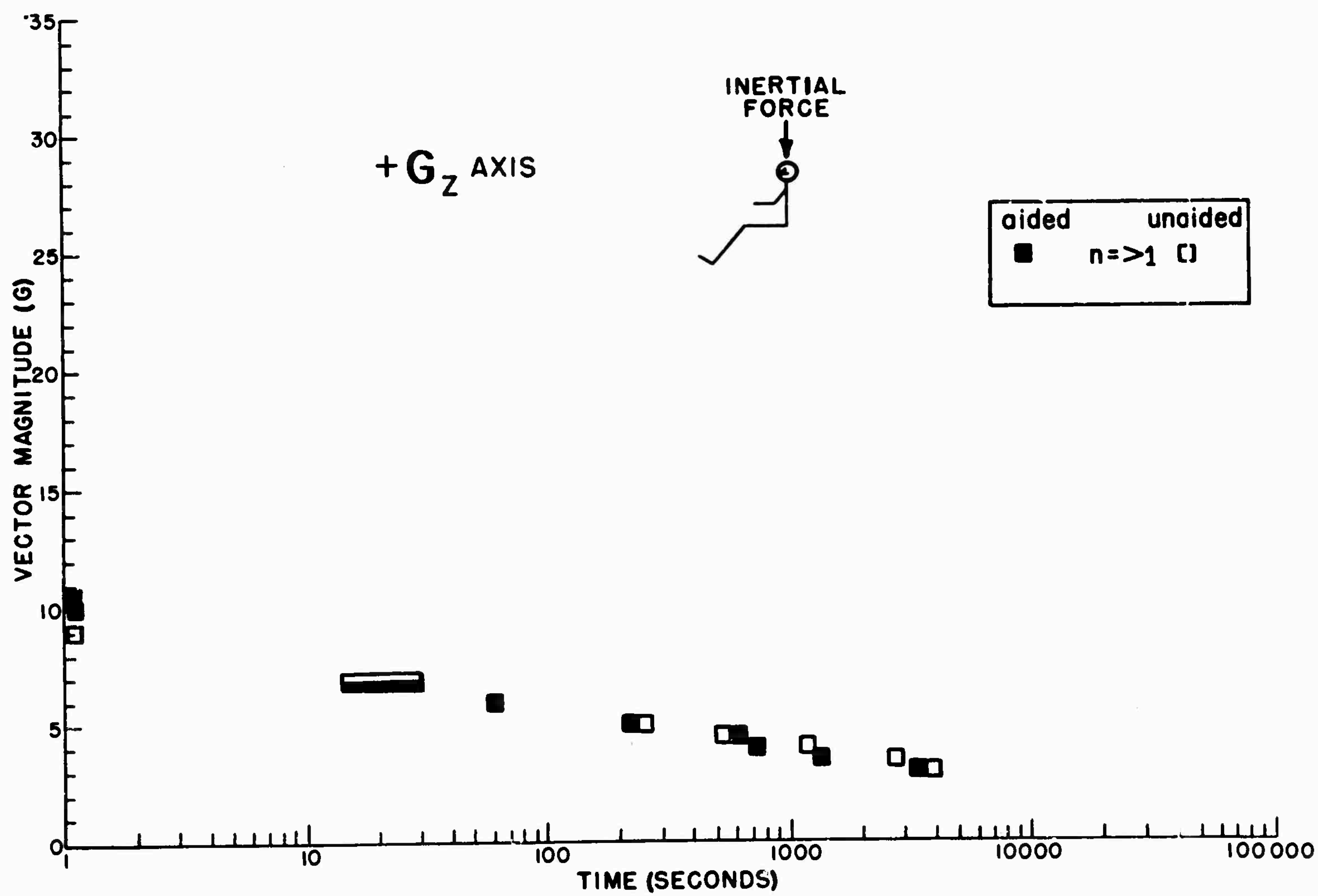
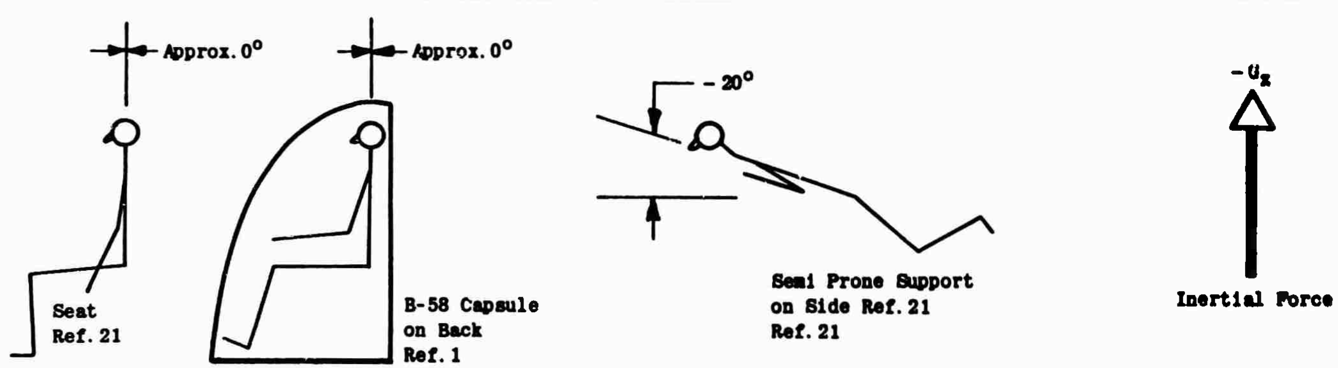


Fig.3 Prolonged acceleration tolerance

TABLE IV

$-G_z$

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
					Unaided n=1					
4.5	5	? Aircraft Maneuvers	?	S?	None	1	None	Aircraft Seat	Lap Belt	28
2.5	56	Usually > than 0.2	Approx. 0°?	S?	None	1	None	Aircraft Seat	Harness	1
2.5	30		Approx. 0°	A	None	1	None	B-58 Capsule on Back	Harness	1
2.0	60		?	A	None	1	None	Turntable	Harness	1
1.5	68		?	A?	None	1	None	Turntable	Harness	1
					Unaided n>1					
3.0	10		Approx. 0°	A	None	5 of 19	None	Seat	Harness	21
2.5	10		Approx. 0°	A	None	19 of 21	None	Seat	Harness	21
					Aided n>1					
5.0	10		Approx. 0°	A	None	15 of 15	Pressure Helmet 25 mm Hg/G	Seat	Harness	21
4.0	10		Approx. 0°	A	None	15 of 15	" " " "	Seat	Harness	21
4.0	10		—20°	A	None	14 of 14	Body Position with Respect to Vector	Semiprone Support	Padded Wood Form	21
3.0	10		Approx. 0°	A	None	29 of 29	Pressure Helmet 25 mm Hg/G	Seat	Harness	21



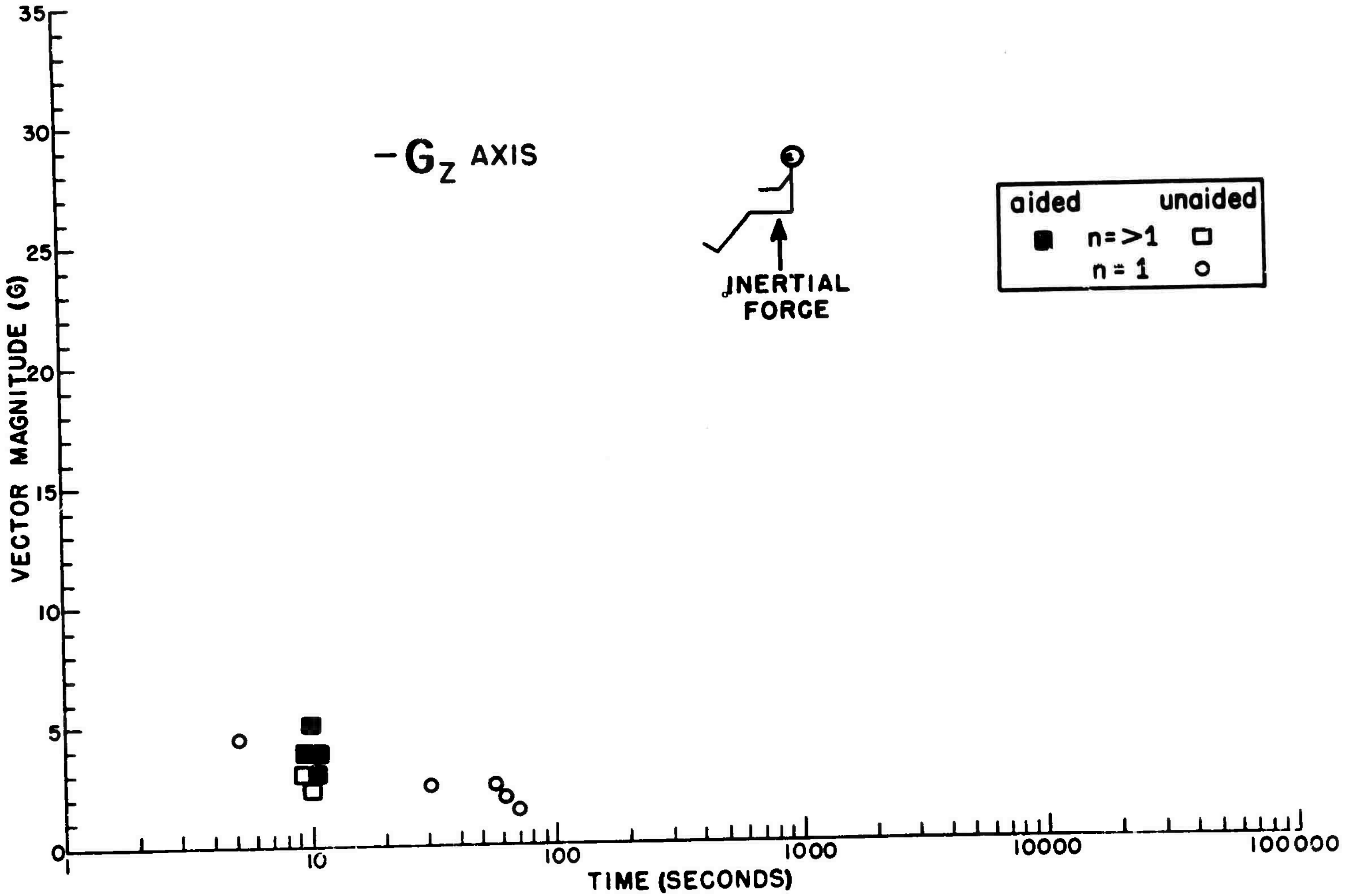
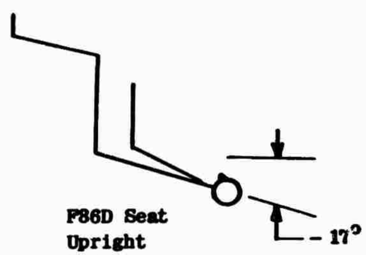


Fig. 4 Prolonged acceleration tolerance

TABLE V

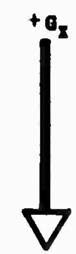
$+G_x$ -17° to 0° Back Angle n = 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Unaided n=1										
12.0	Peak	0.2	0°	S?	None	1	None	Mattress	None	1
10.0	150	?	0°	S	None	1	100% O_2	Foam Matt.	None	25
8.6	Peak	0.5	—17°	S	None	1	None	F-86D Seat	Helmet and Lap Belt	6
8.0	195	?	0°	A	None	1	None	Mattress	None	1
8.0	13	0.5	—17°	S	None	1	None	F-86D Seat	Helmet and Lap Belt	6
6.0	390	"Gradual"	0°	A	None	1	None	Mattress	None	1
4.0	600	"Gradual"	0°	A	None	1	None	Mattress	None	1
3.0	610	"Gradual"	0°	A	None	1	None	Mattress	None	1
Aided n=1										
10.0	328	0.1 to 0.2	0°	S	None	1	19 mm Hg 100% O_2 Positive Pressure Breathing	Foam Matt.	Helmet	25
10.0	252	0.1 to 0.2	0°	S	6 Hour Hemoptysis	1	29 mm Hg 100% O_2 Positive Pressure Breathing	Foam Matt.	Helmet	25



F86D Seat
Upright
Ref. 6

"Mattress"
Ref. 25 & 1



Inertial Force

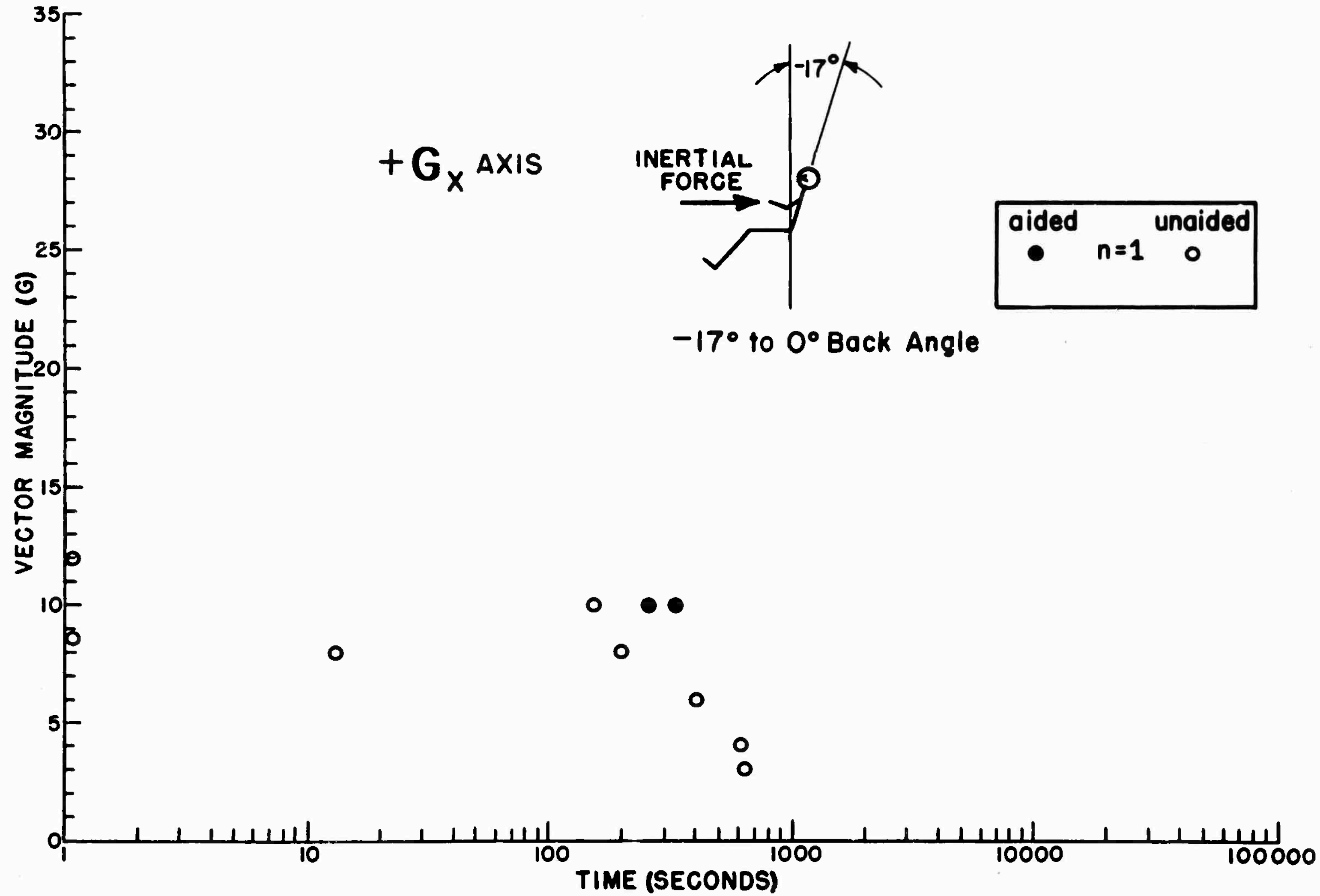
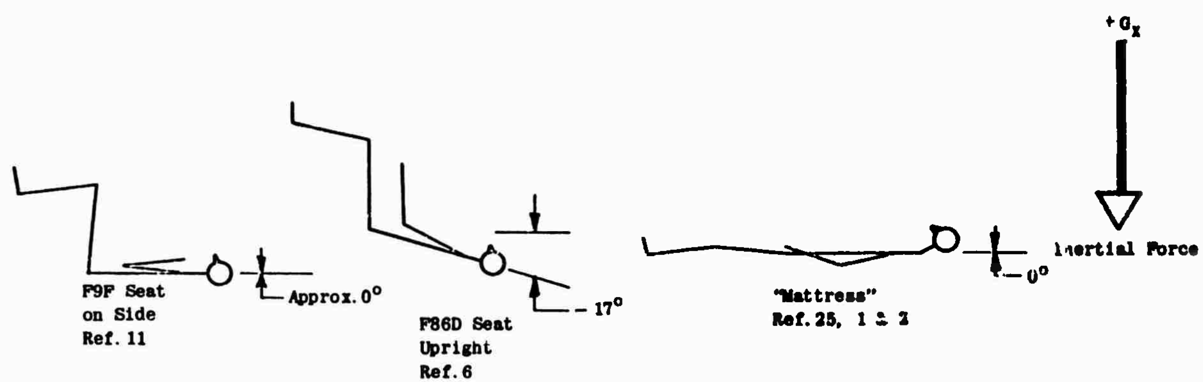


Fig. 5 Prolonged acceleration tolerance

TABLE VI

$+G_x$ -17° to 0° Back Angle n > 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
					Unaided n>1					
15.0	5	8-10	Approx. 0°	Considered as Voluntary Limit	None	5 of 5	None	F-9F Seat on Side	Harness	11
10.0	>130	?	0°	S	None	3 of 9	100% O_2	Foam Matt.	None	25
8.0	>180	0.2	0°	A	None	7	None	Mattress	None	1
8.0	Peak	0.5	−17°	S	None	4	None	F-86D Seat	Helmet and Lap Belt	6
7.0	210	?	0°	A	None	7 of 8	None	Cotton Matt.	None	2
6.0	>360	0.2	0°	A	None	7	None	Mattress	None	1
6.0	270	?	0°	A	None	7 of 8	None	Cotton Matt.	None	2
5.0	330	?	0°	A	None	9 of 9	None	Cotton Matt.	None	2
5.0	>180	0.2	0°	A	None	6	None	Mattress	None	1
4.0	>600	"Gradual"	0°	A	None	7	None	Mattress	None	1
4.0	480	?	0°	A	None	9 of 9	None	Cotton Matt.	None	2
3.0	900	?	0°	A	None	9 of 10	None	Cotton Matt.	None	2
					Aided n>1					
10.0	>200	0.1 to 0.2	0°	S	1 Subject Hemoptysis	4 of 9	19-29 mm Hg 100% O_2 Positive Pressure Breathing	Foam Matt.	None MA-2 Helmet	25



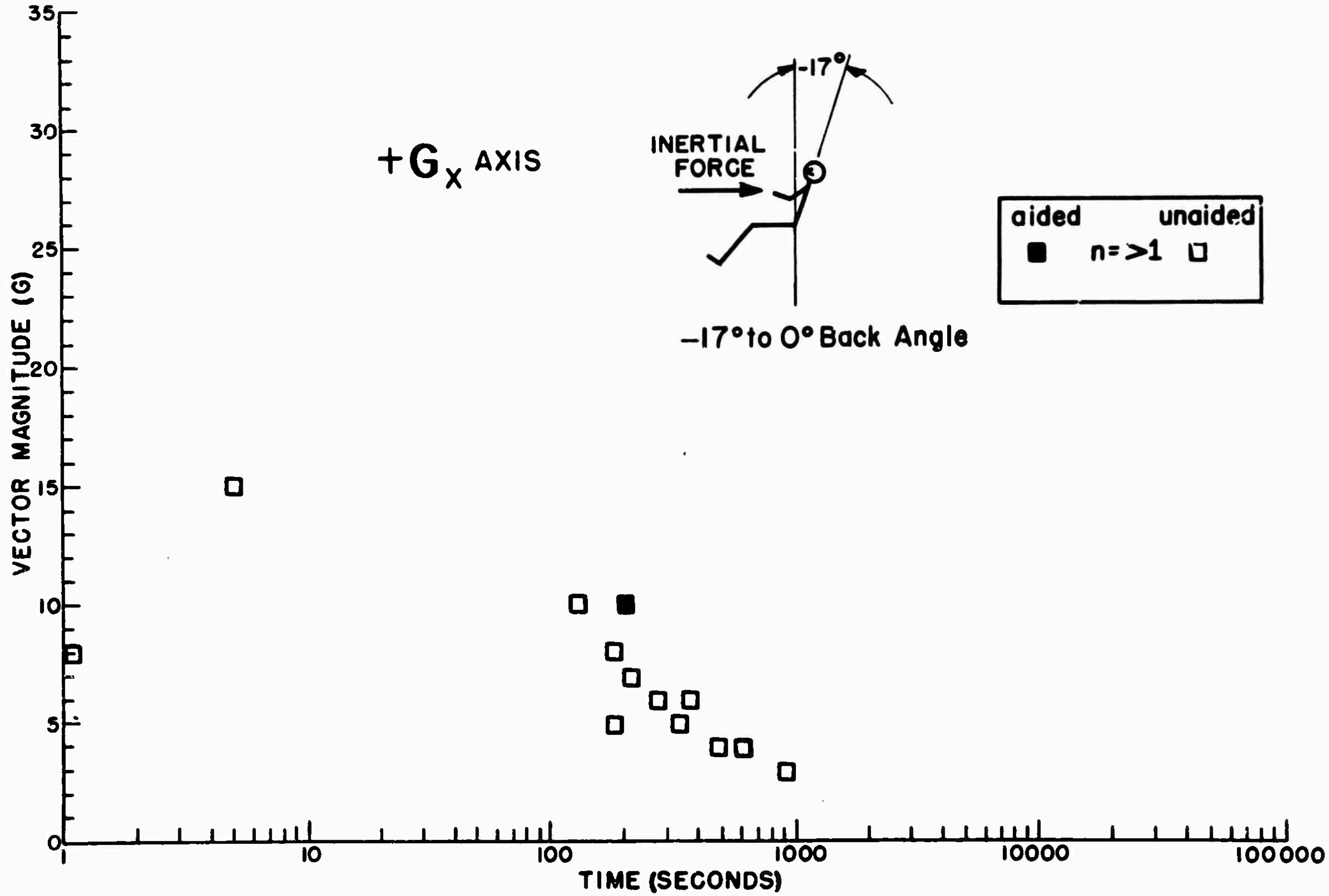
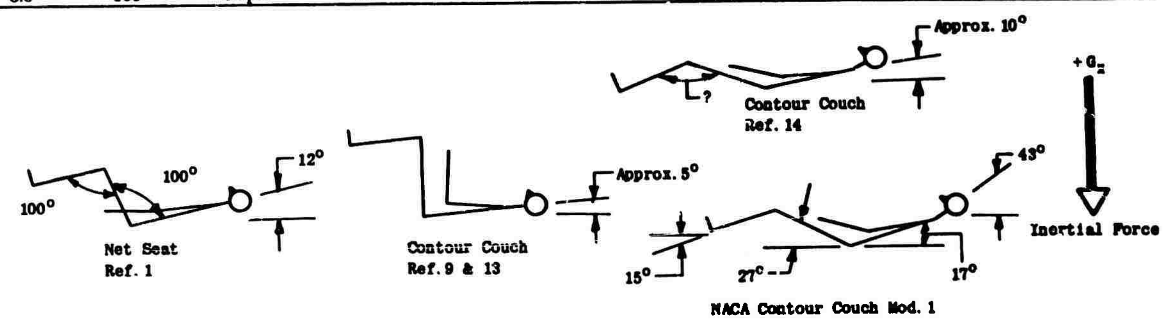


Fig. 6 Prolonged acceleration tolerance

TABLE VII

$+G_x$ 5° to 17° Back Angle n = 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
					Unaided n = 1					
14.0	127	?	Approx. 5°	S?	None	1	None?	Contour Couch	Ref. 23	13
12.0	173	0.2	12°	S?	None	1	None	Net Seat	None	1
12.0	105	"Rapid"	12°	S?	None	1	None	" "	None	1
10.0	90	"Rapid"	12°	A	None	1	None	" "	None	1
9.0	270	0.2	12°	A	None	1	None	" "	None	1
8.0	240	?	12°	A	None	1	None	" "	None	1
8.0	540	0.3	12°	A	None	1	None	" "	None	1
6.0	500	?	12°	A?	None	1	None	" "	None	1
6.0	390	?	Approx. 5°	S?	None	1	None	Modified Mercury Couch	Helmet and Webbing	9
4.5	850	"Gradual"	12°	S?	None	1	None	Net Seat	None	1
4.0	660	?	12°	A	None	1	None	" "	None	1
3.0	1800	0.2	12°	A	None	1	None	" "	None	1
					Aided n = 1					
25.0	Peak	?	Approx. 10°	S?	None	1	Anti-G Suit?	Molded Couch	?	14
23.0	Peak	?	Approx. 10°	A	Inverted T-Wave	1	Anti-G Suit?	" "	?	14
20.7	Peak	1.0	17°	A	None	1 of 2	Anti-G Suit 100% O_2	NACA Mod. 1 Contour Couch	Harness	8
8.0	600	"Rapid"	12°	A	None	1	Positive Pressure Breathing	Net Seat	A-13A Mask	1



Note: One of 2 subjects experienced B.O. at 16 G_x at this 17° back angle (Ref. 8)

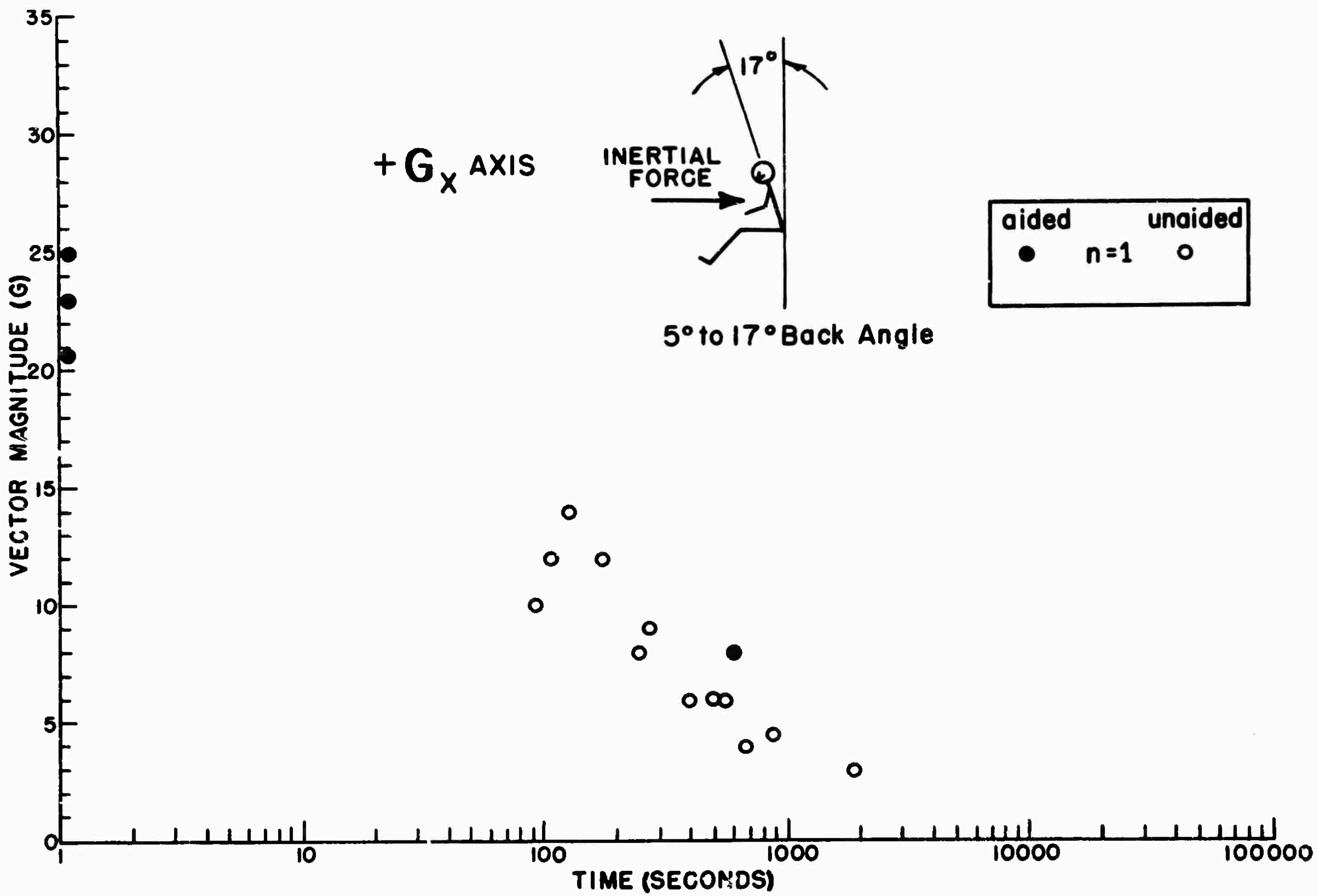
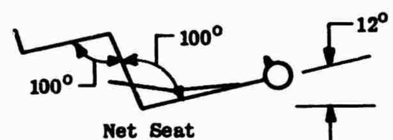


Fig.7 Prolonged acceleration tolerance

TABLE VIII

$+G_x$ 5° to 17° Back Angle n > 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
					Unaided n>1					
16.5	Peak	0.14 to 8.5G, then 0.32 to 16.5G	12°	A	None	5 of 7	None	Net Seat	None	7
12.0	≥110	0.2	12°	S?	None	3	None	" "	None	1
12.0	≥60	"Rapid"	12°	A	None	10	None	" "	None	1
12.0	45	1.0	12°	A	None	8	None	" "	None	1
10.0	≥60	"Rapid"	12°	A	None	3	None	" "	None	1
8.0	≥240	"Rapid"	12°	A	None	2	None	" "	None	1
8.0	≥85	0.2	12°	A	None	10	None	" "	None	1
6.0	>60	0.2	12°	A	None	6	None	" "	None	1
4.0	≥660	"Gradual"	12°	A	None	8	None	" "	None	1
					Aided n>1					
23.0	Peak	?	Approx. 10°	A	1 Subject Inverted T-Wave	2	Anti-G Suit?	Molded Couch	?	14
20.7	Peak	1.0	10°	A	None	2 of 2	Anti-G Suit	NACA Mod. 1 Contour Couch	Harness	8



Net Seat
Ref. 1

Contour Couch
Ref. 14

Modified NACA Contour Couch
Ref. 8

Inertial Force

Note: When back angle was 17°, 2 subjects experienced B.O. at 12 G_x. When back angle was changed to 12°, one subject had B.O. at 16 G_x. (Ref. 7)

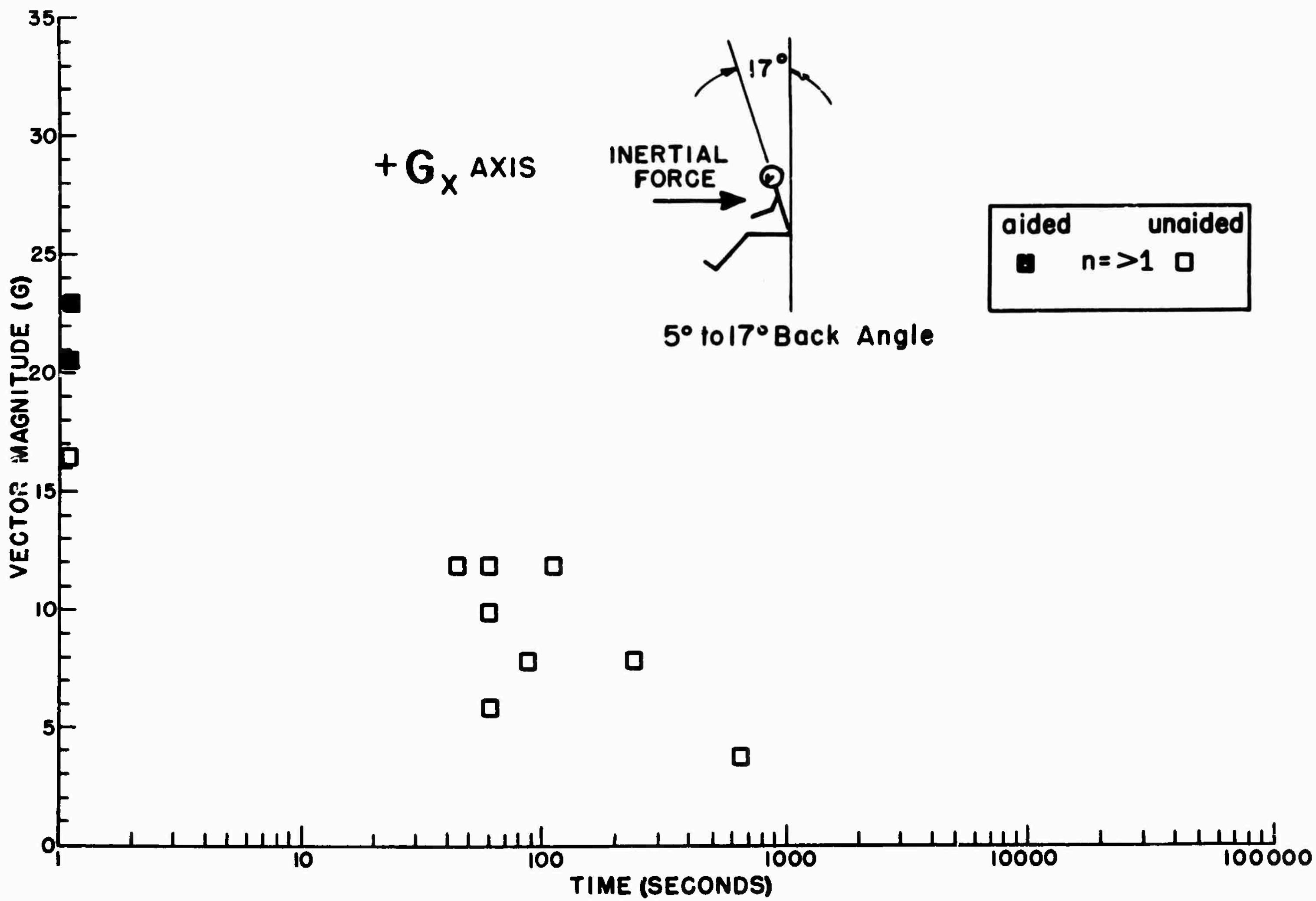


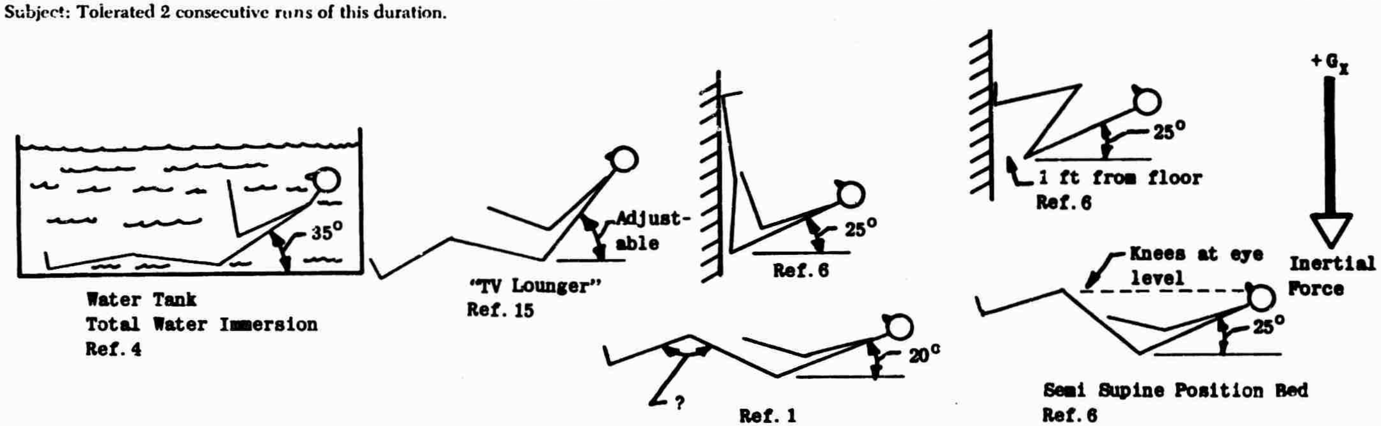
Fig.8 Prolonged acceleration tolerance

TABLE IX

$+G_x$ 20° to 45° Back Angle n = 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Unaided n=1										
12.0	14	0.5	25°	S	None	1 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
11.0	33	0.5	25°	S	None	1 of 7	None	Semisupine-Position Bed	Helmet and Lap Belt	6
9.0	105	?	20°	A	None	1 of 3	None	Semisupine	None?	1
8.0	360*	?	~20°	A	None	1	None	Supine-Rocket	?	1
8.0	100	0.5	25°	S	None	1 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
6.0	395	0.5	25°	S	None	1 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
4.0	660	0.5	25°	S?	24 Hour Leg Pain	1	None	Seated, Legs Flexed	Helmet and Lap Belt	6
2.0	App. 24 Hrs.	?	? Approx. 45° Adjustable	S	Circulatory Deterioration	1	None	TV Lounger	None	15
Aided n=1										
14.0	126	0.2	35°	S	None	1	Total Water Immersion Positive Pressure Breathing	35° Wedge	None	4
12.0	230	0.2	35°	A?	None	1 of 4	Total Water Immersion Positive Pressure Breathing	35° Wedge	None	4
6.0	810	0.2	35°	S?	None	1 of 5	Total Water Immersion Positive Pressure Breathing	35° Wedge	None	4

*Female Subject: Tolerated 2 consecutive runs of this duration.



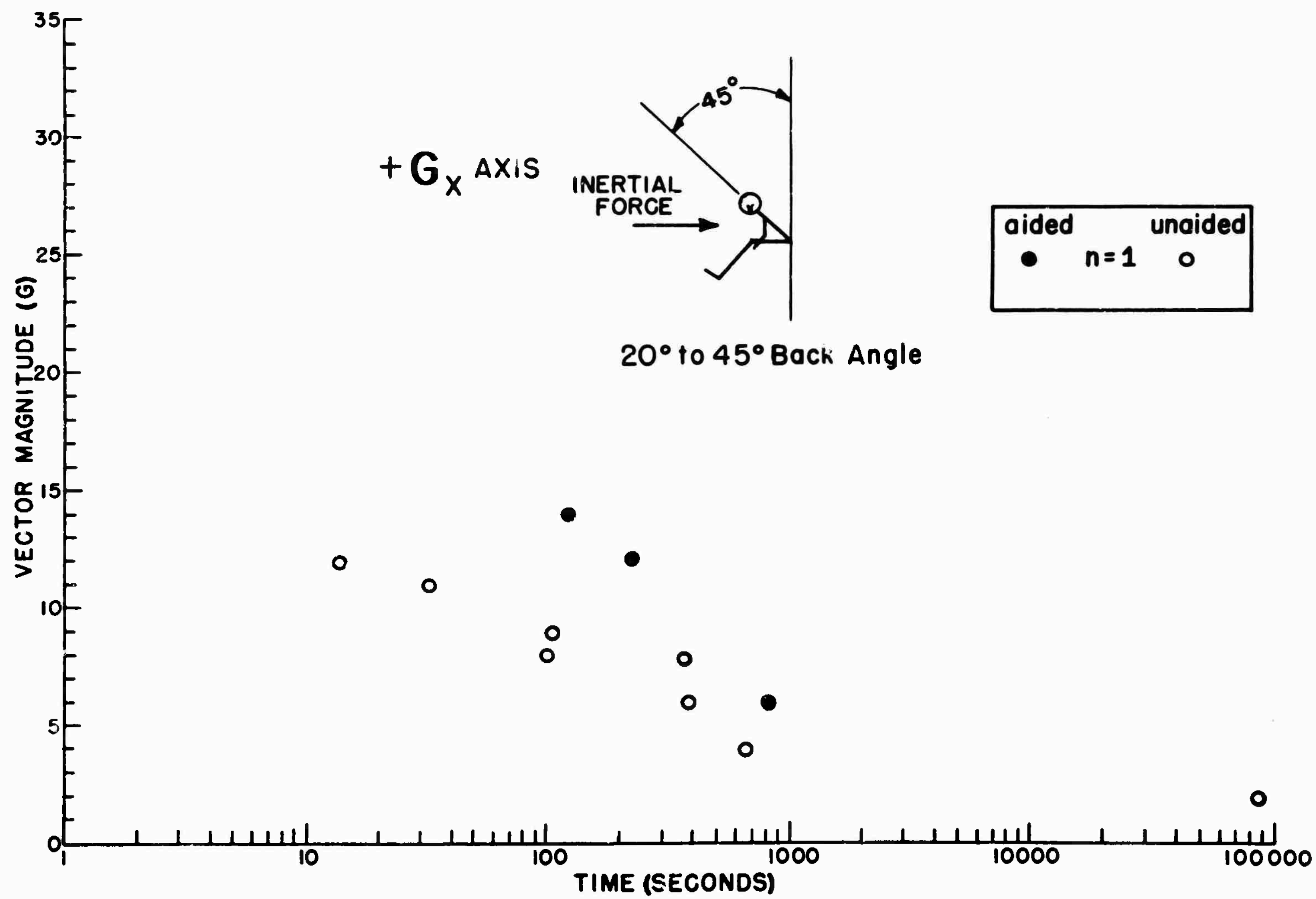
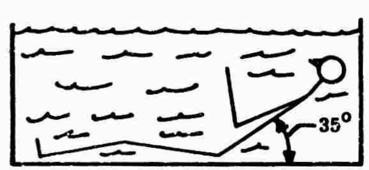


Fig.9 Prolonged acceleration tolerance

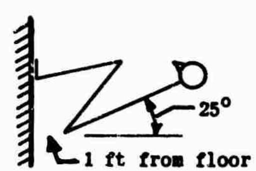
TABLE X

$+G_x$ 20° to 45° Back Angle n > 1

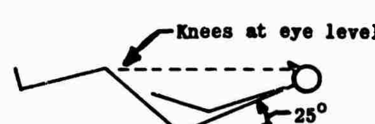
Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
					Unaided n>1					
12.0	2	0.5	25°	S	None	4	None	Seated, Legs Flexed	Helmet and Lap Belt	6
10.0	126	?	20°	S?	None	2 of 3	None	Semisupine-Position Bed	Straps	2
10.0	40	0.5	25°	S	None	2 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
8.7	2	0.5	25°	S	None	2	None	Semisupine-Position Bed	Helmet and Lap Belt	6
8.0	150	?	20°	A	None	3 of 3	None	Semisupine-Position Bed	Straps	2
8.0	$\geq$40	0.5	25°	S	None	6 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
6.0	$\geq$200	0.5	25°	S	None	3 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
4.0	900	0.5	25°	A	None	2 of 6	None	Seated, Legs Flexed	Helmet and Lap Belt	6
					Aided n>1					
10.0	270	0.2	35°	A	None	5 of 6	Total Water Immersion Positive Pressure Breathing	35° Wedge	None	4
8.0	360	0.2	35°	A	None	6 of 6	Total Water Immersion Positive Pressure Breathing	35° Wedge	None	4



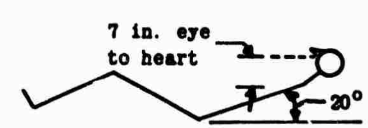
Water Tank
Total Water Immersion
Ref. 4



Ref. 6



Semi Supine Position Bed
Ref. 6



Semi Supine Position Bed
Ref. 2

Inertial Force

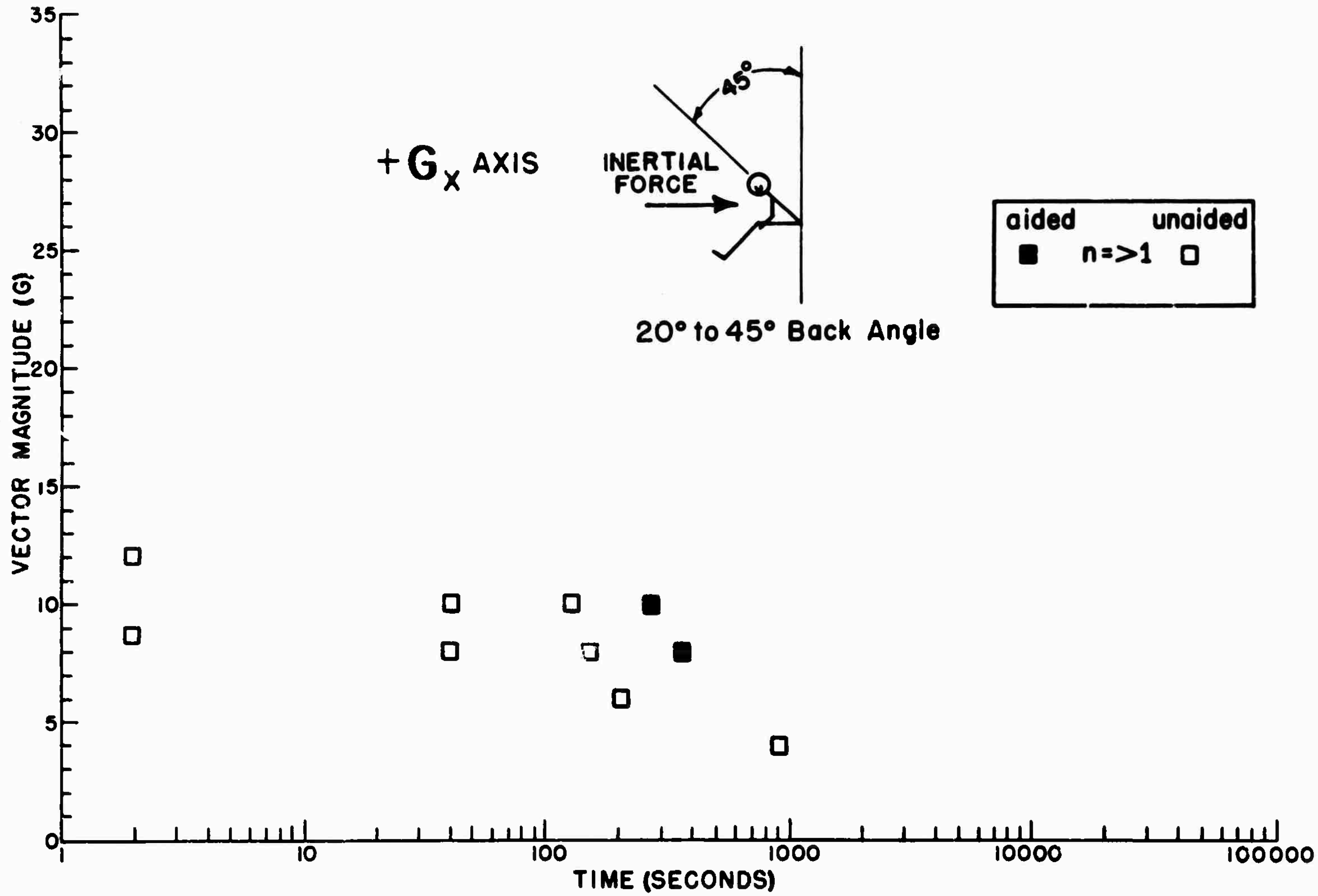
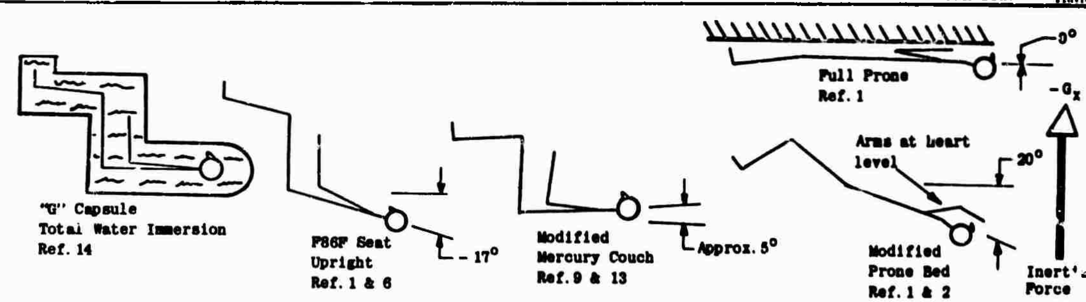


Fig. 10 Prolonged acceleration tolerance

TABLE XI

$-G_x$ n = 1

Vector Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Complete Restraint n = 1										
31.0	5	2.5	Approx. 0°	A?	Blood in Mucous	1	Total Water Immersion Positive Pressure in Lungs	G-Capsule	Water Immersion	14
28.0	Peak?	2.5	Approx. 0°	S	" " "	1	" " " " " " " "	" "	Water Immersion	14
26.0	Peak?	2.5	Approx. 0°	S	" " "	1	" " " " " " " "	" "	Water Immersion	14
12.0	6	0.5	—17°	S	None	1	None	F-86D Seat	Bernadini Restraint	6
11.0	11	0.2	—20°	S?	None	1	None	Semi Prone Bed	None?	1
10.0	90	0.2	—20°	S	None	1	None	Modified Prone Bed	Head Support Helmet	2
10.0	71	?	Approx. 5°	S?	None	1	None	Contour Couch	Ref. 23	13
10.0	18	0.5	—17°	S	None	1	None	F-86D Seat	Bernadini Restraint	6
8.0	65	0.5	—17°	S	None	1	None	F-86D Seat	Bernadini Restraint	6
7.0	300	?	Approx. 5°	S?	None	1	None	Modified Mercury Couch	Helmet and Webbing	9
7.0	240	?	Approx. 5°	S?	None	1	None	Modified Mercury Couch	Helmet and Webbing	9
7.0	210	?	0°	S?	None	1	None	Full Prone on Mat	None	1
6.0	140	0.5	—17°	S	None	1	None	F-86D Seat	Bernadini Restraint	6
5.0	180	0.5	—17°	A	None	1	None	F-86D Seat	Bernadini Restraint	6
4.0	300	0.5	—17°	A	None	1	None	F-86D Seat	Bernadini Restraint	6
3.0	1223	0.5	—17°	S	None	1	None	F-86D Seat	Bernadini Restraint	6
Partial Restraint n = 1										
5.0	18	0.5	—17°	S	None	1	None	F-86D Seat	Integrated Harness	6
3.0	450	0.5?	—17°	S	None	1	None	F-86D Seat?	Integrated Harness	6
2.0	3600	?	—17°	A	None	1	None	F-86D Seat?	Integrated Harness	1
2.0	1800	0.5?	—17°	A	None	1	None	F-86D Seat?	Integrated Harness	6



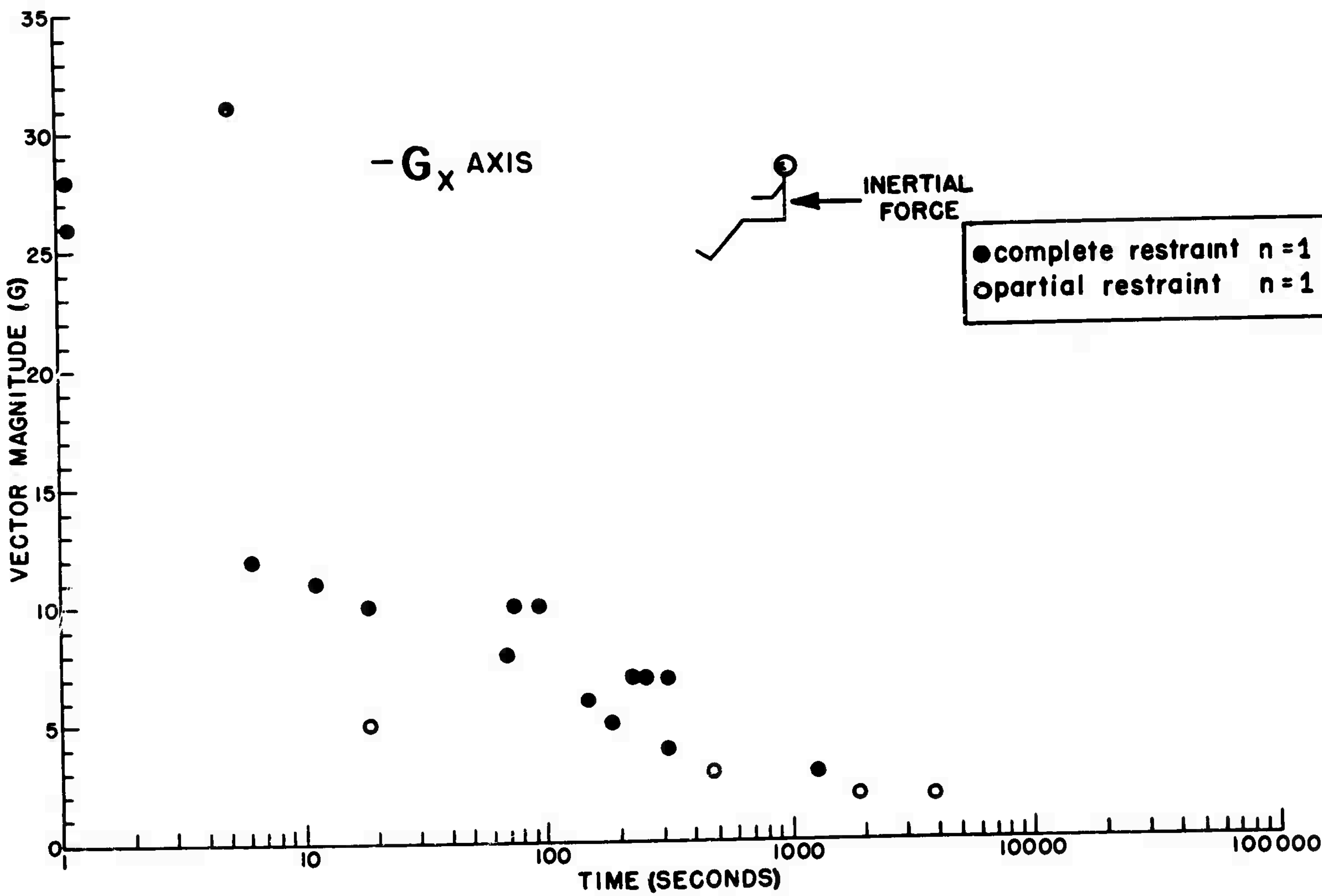
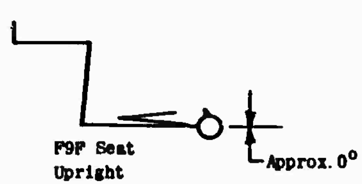


Fig.11 Prolonged acceleration tolerance

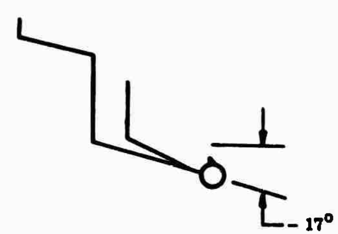
TABLE XII

$-G_x$ n > 1

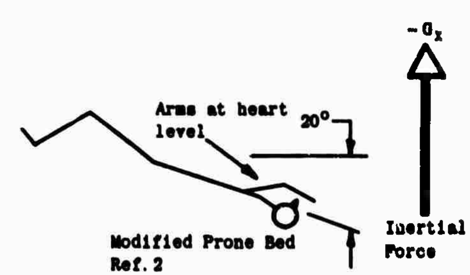
Vector Magnitude (C)	Duration at C (Seconds)	Average Onset (C/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
Complete Restraint n>1										
15.0	5	8-10	Approx. 0°	Voluntary Limit	None	5 of 5	None	F-9F Seat Upright	Padded Barrier	11
12.0	30	0.2	−20°	A	None	2 of 2	None	Modified Prone Bed	Head Support Helmet	2
12.0	≥3	0.5	−17°	S	None	4 of 4	None	F-86D Seat	Bernadini Restraint	6
10.0	120	0.2	−20°	A	None	4 of 9	None	Modified Prone Bed	Head Support Helmet	2
10.0	≥10	0.5	−17°	S	None	3 of 4	None	F-86D Seat	Bernadini Restraint	6
8.0	120	0.2	−20°	A	None	13 of 13	None	Modified Prone Bed	Head Support Helmet	2
8.0	>30	0.5	−17°	S	None	3 of 4	None	F-86D Seat	Bernadini Restraint	6
6.0	>50	0.5	−17°	S	None	4 of 4	None	F-86D Seat	Bernadini Restraint	6
5.0	≥80	0.5	−17°	S	None	4 of 4	None	F-86D Seat	Bernadini Restraint	6
4.0	>240	0.5	−17°	S	None	3 of 4	None	F-86D Seat	Bernadini Restraint	6
3.0	≥1200	0.5	−17°	A	None	2 of 4	None	F-86D Seat	Bernadini Restraint	6
3.0	900	0.2	−20°	A	None	10 of 13	None	Modified Prone Bed	Head Support Helmet	2
2.0	1200	0.5	−17°	A	None	2 of 2	None	F-86D Seat	Bernadini Restraint	6
Partial Restraint n>1										
5.0	>5	0.5	−17°	S	None	4 of 5	None	F-86D Seat	Integrated Harness	6
3.0	>300	0.5?	−17°	S	None	4 of 4	None	F-86D Seat?	Integrated Harness	6
2.0	>1000	0.5?	−17°	S	None	2 of 3	None	F-86D Seat?	Integrated Harness	6



F9F Seat
Upright
Ref. 11



F86D Seat
Upright
Ref. 6



Modified Prone Bed
Ref. 2

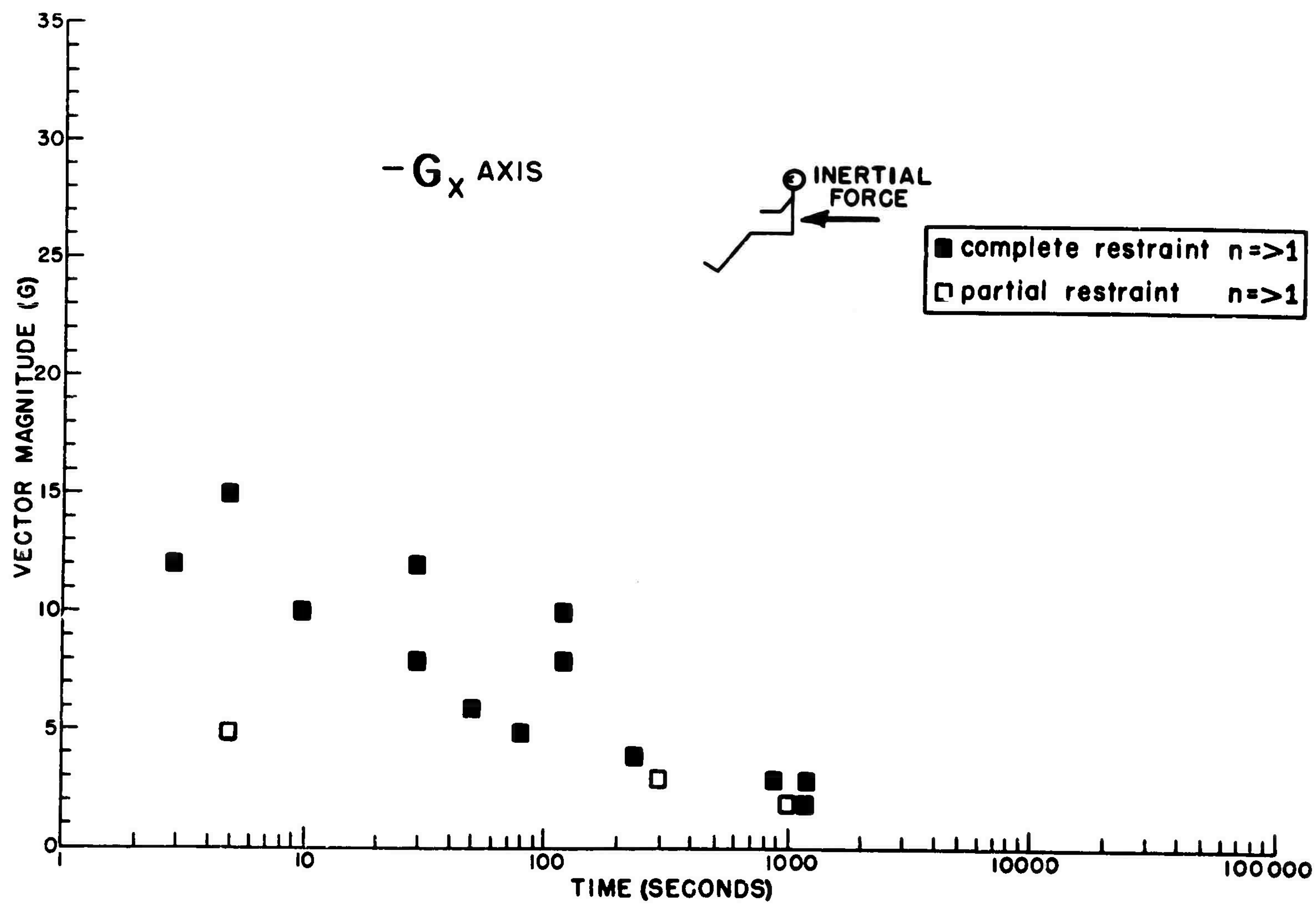
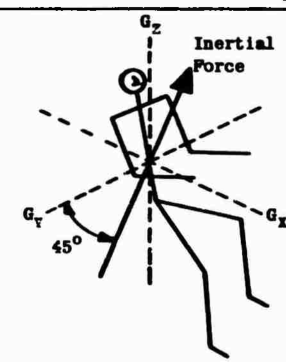


Fig. 12 Prolonged acceleration tolerance

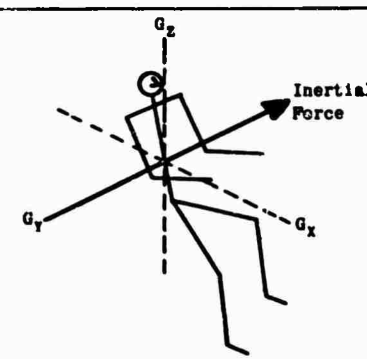
TABLE VIII

$\pm G_y$

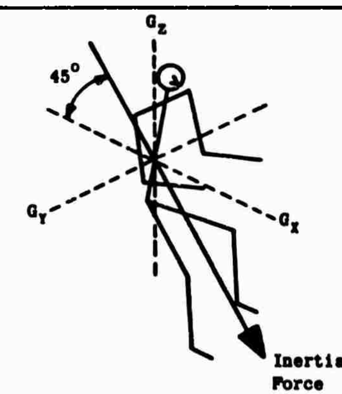
Resultant Vector Magnitude (G)	Component Vector(s) Magnitude (G)	Duration at G (Seconds)	Average Onset (G/Second)	Back Angle (Degrees)	Cause of Termination	Trauma	Number of Subjects Attaining	Countermeasures	Support	Restraint	Reference
6.6	±?6.6 Gy	35	0.2	—13°	A	None	1	None	Modified Aircraft Seat	Harness Suit	1
5.6	±?5.6 Gy	25	0.2	—13°	A	None	1	None			1
5.4	±?5.4 Gy	40	0.2	—13°	A	None	1	None	(See Ref. 17 for		1
5.0	±?5.0 Gy	60	0.2	—13°	A	None	1	None	other particulars)		1
4.5	±?4.5 Gy	30	0.2	—13°	A	None	1	None			1
Combinations of Various Vectors											
10.0	+7.1 Gx ±?7.1 Gy	1	?	—13°	S?	None	1	None	Aircraft Seat Rotated 45° from Centrifuge Arm Axis	Harness Suit?	1
6.0	+4.2 Gx ±?4.2 Gy	15	?	—13°	A	None	1	None			1
4.0	+2.8 Gx ±?2.8 Gy	15	?	—13°	A	None	1	None			1
8.5	+6.0 Gz −6.0 Gx	20	?	Approx. 5°	S	None	1	Anti-G Suit	Modified Mercury Couch	Helmet and Webbing	22
7.1	+5.0 Gz −5.0 Gx	162	?	Approx. 5°	S	None	1	" " "	" " "	" " "	22
5.6	+4.0 Gz −4.0 Gx	348	?	Approx. 5°	S	None	1	" " "	" " "	" " "	22



Resultant vector from equal $+G_X$ & $+G_Y$ components. -13° back angle. Ref. 1



Resultant vector from $+G_Y$. -13° back angle Ref. 1 & 17



Resultant vector from equal $-G_X$ & $+G_Z$ components. Ref. 22

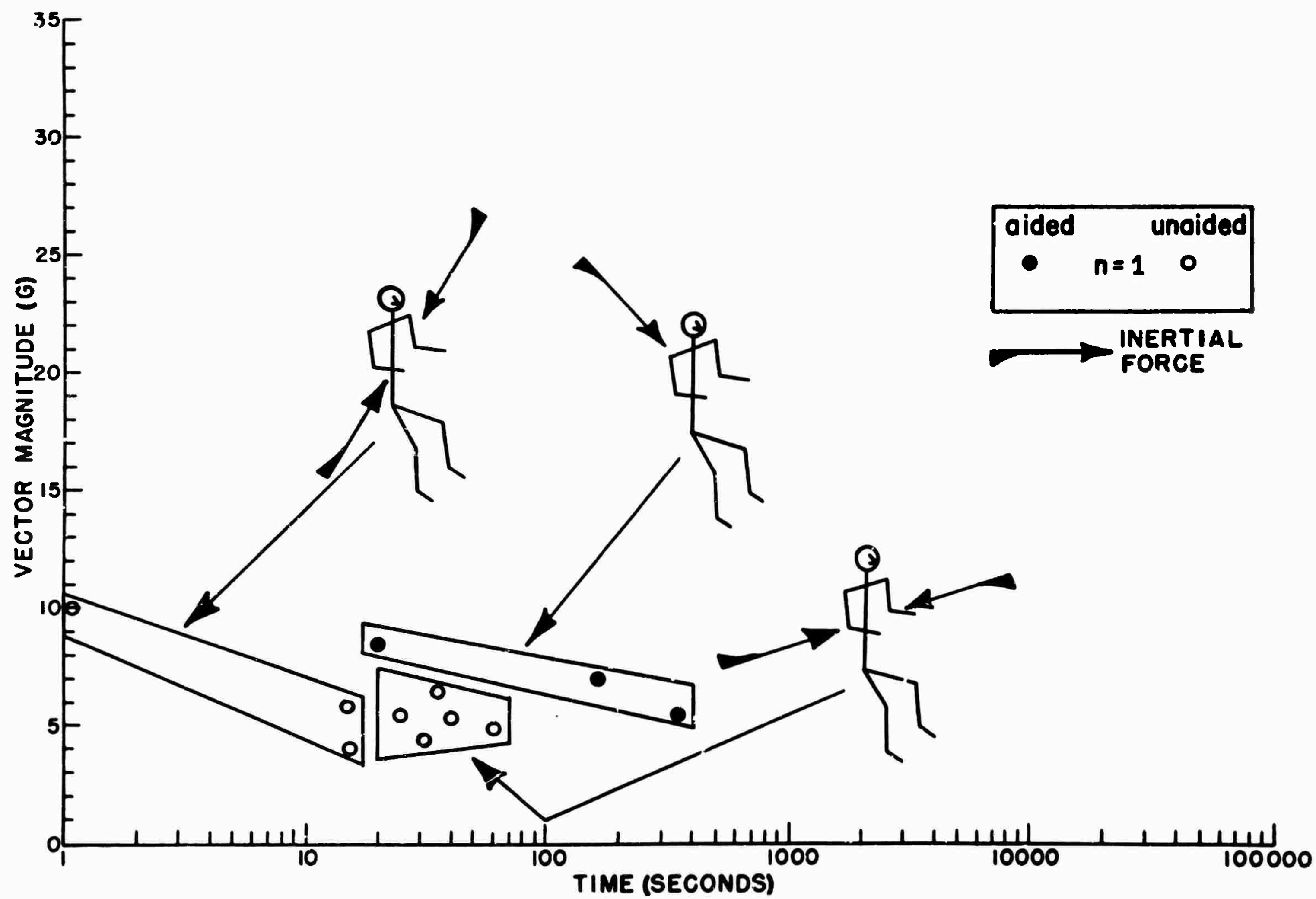


Fig.13 Prolonged acceleration tolerance. Combinations of various vectors

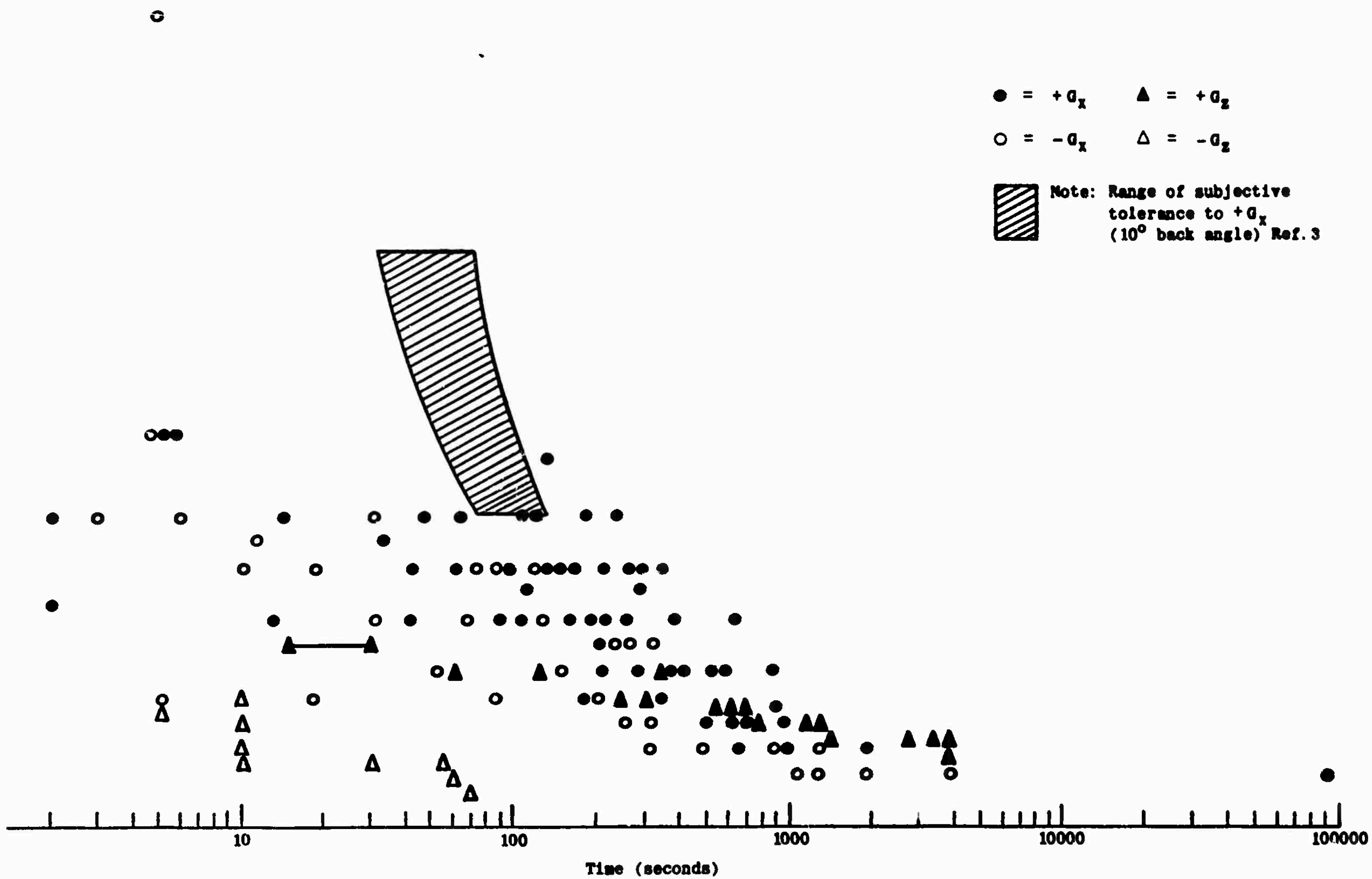


Fig. 14 Prolonged acceleration tolerance. Summary: $\pm G_x$ and $\pm G_z$

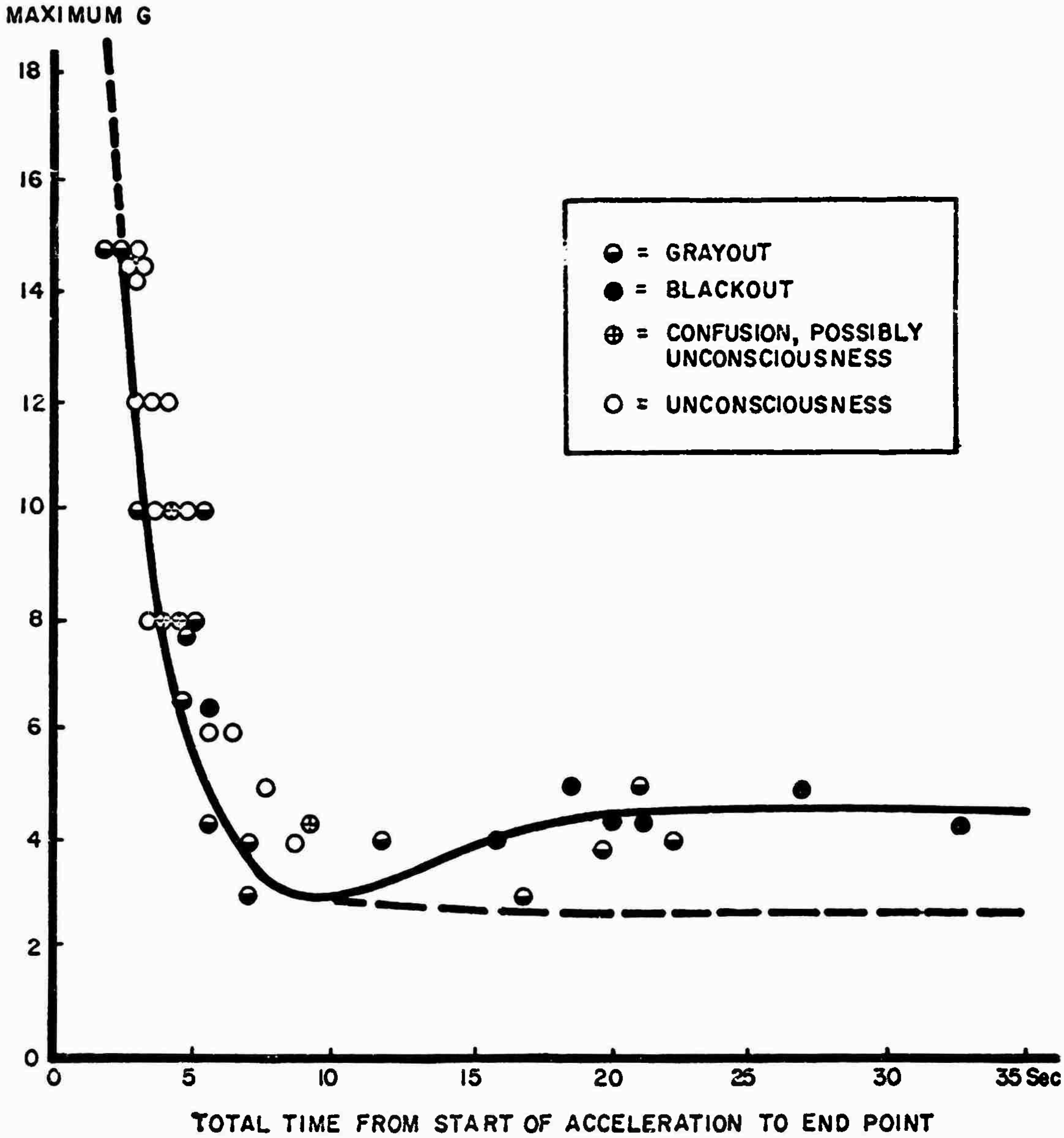


Fig.15 Human tolerance to $+G_z$. (Redrawn from Reference 24)

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TURKEY TURQUIE	Ministry of National Defence Ankara Attn: AGARD National Delegate
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